A DENDROCLIMATOLOGICAL STUDY OF LONG-TERM GROWTH PATTERNS

OF YELLOW-CEDAR TREES IN SOUTHEAST ALASKA

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A

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By

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Abstract

Yellow-cedar is a very long-lived, commercially important tree species found along the coasts of Southeast Alaska and also in small populations in Prince William Sound. However, this is the first study of the tree's annual ring growth patterns in the region. Tree cores were collected from over 400 trees across a large latitudinal gradient and cross-dated using standard dendrochronological techniques. Radial tree-ring growth was measured and compared to reconstructed weather station data to gain a better understanding of the climatic conditions favoring yellow-cedar growth. We found consistent, significant positive correlations between ring widths and mean monthly temperatures in August, previous January, and previous December, and negative relationships with May and December precipitation. Climate indices we created using these variables explain approximately 25% of growth variability in five distinct yellow-cedar populations. Long-term growth patterns in tree populations going back three centuries were similar across all sites, specifically the sustained below mean growth during the 1800s. Yellow-cedar at the northern limits of its distribution shows a common growth signal which may indicate the influence of larger pressure anomalies, such as El Niño-Southern Oscillation (ENSO), on the climate factors affecting the trees.

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Introduction

My XTRA-TUF® boots sink into the spongy mat that makes up the floor of the muskeg. I turn around to watch it spring back into place where I last stepped, erasing any sign of my passing. The sky is overcast and the air is thick with humidity. I feel wet everywhere, my fingers saturated as if a moment ago I had gotten out of the bathtub. My back is sticky with sweat where it contacts the backpack filled with wood glue, beeswax, clothespins, and poplar slats sticking up out between the zippers. I am following my research partner Colin as he makes his way toward the next cedar we are going to core. For all of our experience and expertise we still cannot differentiate yellow-cedar and western redcedar until we actually see a portion of secondary xylem. We have mistaken too many redcedar for the sought-after yellow-cedar to ever completely trust our own judgment again.

I remove a slotted mounting board from my pack as Colin begins to drill the increment borer through the shaggy bark of the tree. I listen to the creak of the borer entering the tree as I go through my preparation-for-the-core routine. I tell him when the large tree has been finally pierced. As he removes the spoon with the long, straw-sized piece of wood, I hope that it is the tree we are after. It is the straight-grained, pale white wood of a yellow-cedar! I can smell the distinctive odor fill the air as I clip the core to the glued slat, eyeing the faint annual growth rings for some clue as to how old the tree is and how well it has been growing. I know there will be plenty of time spent later staring at this small piece of wood through a microscope back at the laboratory in Fairbanks. So much valuable information in such an eloquent little package, a portion of Southeast Alaska that we can take with us to help tell us the story of the tree and the region.

Nobody is sure why yellow-cedar trees have been dying across the Tongass National Forest over the past century. The decline phenomenon cannot wholly be explained by insect outbreaks, fungal pathogens, or bog expansion. Paul Hennon and his colleagues at the USDA Forest Service have been exhaustively studying this species for over two decades and they believe it may be driven by climatic factors. They speculate that yellow-cedar may experience root damage from spring freeze events when the trees deharden early in response to late-winter warmth. That is where I come in. My research focuses on the attempt to correlate yellow-cedar tree-ring chronologies with historic weather records from Southeast Alaska. I will not be able to solve the mystery alone, but I supply a valuable piece of information in determining what climate factors that live yellow-cedar trees respond to when growing.

My thesis is the result of months of collaborative work in the field and the laboratory. It is separated into three chapters written to stand alone, although the work was integrated and each part essential to the next. My research partner, Colin Beier, is using the same tree cores to attempt to determine what climate factors may be driving the yellow-cedar decline phenomenon. My thesis is centered on climate effects on live tree growth patterns in the past three centuries, without an attempt to explain the connection to cedar decline.

The first chapter is simply a presentation of the weather station records that we compiled, combined, and filled in the missing data for in order to run later correlations. We primarily used monthly mean temperatures and monthly precipitation totals to compare with annual tree-ring growth, so that is how the data is presented. We believe this to be the first comprehensive comparison of all the major weather stations in Southeast Alaska. It is our hope the reconstructed datasets found in the Appendix may prove useful for future researchers in the region.

Chapter 2 is a standard tree-ring study done to compare detrended ring width indices with climate factors. It focuses on determining which monthly temperature and precipitation variables have the highest correlation with year-to-year ring growth variability. We tested for possible cumulative effects and unique predictive power in producing a climate predictor index for annual yellow-cedar growth at the northern extent of its distribution.

The final chapter is another, more unique comparison of climate and tree-rings, focusing on extremes of growth and weather patterns, in addition to presenting the oldest chronologies available. It is separated from the previous chapter because it centers on weather event-based ring formation rather than the more traditional approach to dendroclimatology using long-term variation in a few predictor months. The specific large and small "marker" rings seen in individual trees can provide a clue into what extreme weather events may directly impact yellow-cedar growth. The chronologies composed of the oldest trees sampled go back 300 and 400 years to show the consistent growing patterns seen in the trees throughout the region.

The three chapters can be read separately or as a whole, with each containing unique results and figures. If you are interested in learning more about yellow-cedar decline in Southeast Alaska, please consult the work of Paul Hennon, Dave D'Amore, and Colin Beier.

Chapter 1. Climate station comparability of Southeast Alaska 1832-2004

Abstract

Southeast Alaska has some of the oldest continuous climate records in the Pacific Northwest, beginning in 1832 at Sitka and the early 1900s elsewhere. Their value to this thesis lies in the ability to compare to yellow-cedar tree rings from the nineteenth century. Problems with these records include changes in recording location and technique over time, as well as gaps in recording. We found that stations across the region had highly significant correlation with one another and used predictor stations to systematically reconstruct missing values in the station records. The reconstructed data presented here may be useful in other research contexts. All stations examined show below mean growing year temperature (September-August) from the mid-1960s to mid-1970s and sustained above mean temperatures since 1977, matching a notable shift in the climate regime of the eastern Pacific and northwest North America documented to have begun at that time.

Introduction

Southeast Alaska is a unique region of heavily-forested islands, sheltered ocean channels, dramatic mountain peaks, glaciers, and extensive old conifer forests. It has been the home of aboriginal peoples, including the Tlingit and Haida, for thousands of years (Haycox 2002). In the eighteenth century, European naval powers became interested in the region, with famous captains including Vitus Bering, James Cook, Jean de la Perouse, and Alejandro Malaspina helping to chart its waters. The Russians were the first to significantly colonize the area, with Aleksandr Baranov establishing a post at Novo

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Arkangel'sk, the site of modern day Sitka, Alaska (Figure 1.1). Daily records of high and low temperatures there commenced in 1828, and precipitation measurements were added in 1842 (Table 1.1). The United States purchased Alaska from Russia in 1867. Weather measurements continued following the purchase until the U.S. Army withdrawal in 1877 (Haycox 2002).

On the heels of the Klondike Gold Rush in 1899, weather station recording restarted at the Sitka Magnetic Observatory and became more consistent at Juneau, the site of a minor gold strike in 1880 (Table 1.1). Stations at the Gold Rush ports of Haines and Skagway have records going back to the Klondike Gold Rush time period as well (Figure 1.1). Ketchikan, Wrangell, and Petersburg also have station record length in excess of 75 years. Stations at Yakutat, Annette Island, Sitka Airport on Japonski Island, and Juneau Airport all begin in the 1940s.

Many studies have analyzed climate patterns of the Pacific Coast of North America (Roden 1989, Wiles et al. 1996, Ware and Thomson 1999). They found correlations between regional weather records and tree-ring chronologies, El Niño-Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO). Such studies have typically enlisted the Sitka weather station (combination of all its locations) as a proxy for the entire region of Southeast Alaska due to the unique length of record that can be assembled by combining locations with "Sitka" in the name. However, there are problems associated with these records due to changes in recording techniques and locations (Roden 1989, Juday 1984). The weather in Southeast Alaska can be dramatically different within the span of a few kilometers due to the complex topography and maritime influence of the many fjords and bays.

No published studies compare climate station records from throughout Southeast Alaska to evaluate the consistency of weather patterns over time. This paper will focus exclusively on reconstructing the weather station datasets of Southeast Alaska and is meant to present a general overview of regional climate characteristics, as well as point out some problems using these datasets, especially in dendroclimatological analysis.

Methods

The climate data used in our research was aimed at comparison to tree rings. In this context, it was our goal to summarize daily records into monthly metrics which could be easily compared to annual ring growth (Cook and Kairiukstis 1992).

The Alaska Climate Research Center in Fairbanks, Alaska provided historical data from weather stations in Southeast Alaska that go back to 1899 at Sitka, Alaska and the early 1900s for other stations (Table 1.1). Dr. Gunnar Roden (1989, NWS 2006) supplied historic data from Sitka Magnetic Observatory going back to 1828. Gaps in weather data create particular problems in comparison analysis involving long-term continuous response variables, such as tree-ring chronologies. As a result, we applied techniques to reconstruct missing weather observations.

Another potential problem in the use of southeast Alaska weather station records is that collection locations and techniques changed over time, especially prior to about 1950 when most records meet the standards of a First Order weather station (ACRC 2006). These changes typically do not have a major effect after data are pooled into monthly summary statistics, as used in this study. Stations at Haines and Skagway were not included in this comparison because they exhibit the strong influence of interior weather patterns (Juday 1984).

Each weather station's daily high and low temperature (original measurements recorded in degrees Fahrenheit) and precipitation total (inches) was used to compile monthly mean temperature, monthly total precipitation, and growing season length. For daily temperature data, we filled missing entries in the case of a one to three day gap by inserting an average of the two adjacent days. This rapid averaging technique allowed coverage of hundreds of short gaps, and typically has an impact of less than 0.1 degree Fahrenheit error either direction on monthly mean temperatures. Calculated monthly averages from a given station were not used if a single month contained a gap of more than three consecutive days or more than five days total Gaps of 4 or more days are more likely to provide sufficient time to allow an entire weather front to move through a station location, in which case the temperatures before and after frontal passage would have limited value in reconstructing the missing values. In such cases we reconstructed the monthly mean temperature using the closest available station with the highest correlation (Table. 1.2) as a predictor (Juday 1984). Reconstructed values were calculated by using the corresponding value of the predictor station and adding the average difference between the two stations from four years of the same month showing similar mean temperatures at the predictor station. For precipitation data, we changed missing entries to null values, and monthly totals were only used if they had less than three missing days. Precipitation totals include both rainfall and snowfall. In addition, snowfall totals were obtained from a NOAA sponsored online database (NWS 2006).

To create the most homogenous long-term records possible, we combined two nearby stations at Sitka Airport using Sitka Magnetic Observatory, Juneau Airport using Juneau Downtown, Wrangell using Petersburg, and Annette Island using Ketchikan. We took the overlapping data from the two stations to create an average difference for each month and then applied that transformation to the secondary station to maintain a similar scale. We then added those differences to the past values to simulate what the recording would have been at the modern station. Thereafter, only the new datasets were used in analysis.

Nineteenth century Sitka records were taken at a small, exposed loghouse on Japonski Island (Roden 1989). The daily means were calculated using from 4 to 24 observations per day. The longest period of one consistent calculation was 1832 to 1845 when four daily observations were averaged. The only data available from NOAA (either taken by American observers or records in American custody from Russian sources) for this period are monthly means. Records prior to 1832 were omitted from analyses as they were not recorded in a systematic way and were extremely high compared to other values (Roden 1989). The annual mean temperature graph created from these data needs to be interpreted with caution.

Annual climate values were compiled to check for longer term trends such as El Niño-Southern Oscillation (ENSO) and Pacific Decal Oscillation (PDO). We used these values to calculate the rate of warming since 1922 and converted it to a per century scale. Growing year means for temperature and precipitation were calculated using the twelve months September to August. Since the purpose of reconstructing this weather station data was for tree-ring comparisons, we chose the last month of diameter growth in August (Laroque and Smith 1999) as the cutoff for growing year. There is no reason to believe the growth year basis of calculating mean annual temperatures produces results significantly different than the more traditional calendar year approach. Summer (June, July, August) and winter (December, January, February) mean temperature was also calculated for each station for comparison purposes.

Before conducting any type of reconstructions, we calculated Pearson correlations to compare stations (Table 1.2) to determine their usefulness as predictor stations for each other. After reconstruction, Pearson correlations were calculated to determine the correspondence between monthly temperature, precipitation, and snowfall values at a given station (Table 1.3). Only after all of the above reconstructions were completed were temperature values converted from the original degrees Fahrenheit to Celsius and precipitation levels from inches to centimeters.

Results and Discussion

Unreconstructed temperature records among all weather stations in Southeast Alaska were significantly correlated ($p<0.05$; Table 1.2). The lowest correlations were with the Ketchikan station, possibly due to its fragmentary records. Figure 1.2 visually displays the consistency between the five reconstructed station means. Two characteristic features of the consistency among stations are high positive temperature anomalies in 1926, 1958, 1970, 1977, and 1998 and negative anomalies in 1933, 1956, and 1982. There was a notable sustained low in mean growing year temperatures from 1971-76 at all stations, and 1965-76 at Wrangell, Juneau, and Yakutat.

Annette Island and Juneau experienced a slight increase in temperature over time, especially since the 1977 climate regime shift (Ware and Thomson 1999). Rate of warming since 1922 was 1.00556°C per century at Annette Island and 1.35556°C per century at Juneau, but only 0.28333°C at Wrangell and actually decreased -0.93333°C at Sitka. Annette Island and Sitka, located in the southern and outer coastal portions of the region respectively, were consistently warmer than the other three stations. However, temperatures at Sitka switched from typically warmer to cooler than Annette Island after 1942 (Figure 1.2). It is unclear whether the change resulted from the 1942 move of the station 1.6 km northeast and 13 m uphill (ACRC 2006), or possibly from an isolated warming trend at Annette Island over that same time period. To avoid this effect Juday (1984) applied a transformation to the Sitka data from 1899 to 1942 of approximately minus-2 degrees Celsius.

Due to variation in measurement technique and locality over time, Figure 1.6 probably does not represent the a consistently comparable record of temperature over the entire time depicted, but is helpful for demonstrating general trends at Sitka. Sitka, and presumably most of Southeast Alaska, experienced a notable low growing year temperature in 1877. The Sitka record shows particularly high values in 1870, 1915 and

1926 (Figure 1.6). Growing year mean temperature at Sitka appeared to be consistently higher since 1977 than in the thirty years prior. This is consistent with a broad climate regime shift, which is thought to have occurred at that time (Ware and Thomson 1999), and appeared in the other station records as well (Figure 1.2).

Among the 5 stations summer (Figure 1.3) and winter (Figure 1.4) mean temperature are both significantly correlated to mean annual temperature ($p<0.01$). Neither seasonal mean shows a dominant influence over the annual mean, with the exception that winter temperatures were the driving force for the cool period of annual mean temperatures between 1965 and 1976. One drawback to using mean temperature is that it does not account for the range of temperature experienced. Weather patterns in Southeast Alaska are strongly influenced by continental, high pressure and maritime, low pressure systems. Under the maritime influence there is a lower range between the daily high and low than under continental systems. So it is possible to produce the same annual mean from a maritime regime of minimal daily and seasonal temperature range and from a more continental regime with respectively greater temperature ranges, while the ecological effect of the two different regimes on the trees and forest ecosystem are likely to be different.

Precipitation totals from station to station varied widely (Figure 1.5) and correlations among stations were not as strong as those among station temperature records. Wrangell was left out of the analysis because of there were too many gaps in its precipitation records. Specific high precipitation years across the set of 5 stations include 1949, 1981, 1992, and 2000. Low precipitation totals occurred in 1951 and 1974. Yakutat and Annette Island consistently received more precipitation than Sitka and Juneau, with Yakutat most often experiencing the highest totals.

Due to limited data on total precipitation and snowfall prior to 1948, correlations in Table 1.3 were only run for the period since then. During the period of comparison, May through August temperatures were inversely correlated with precipitation (Table 1.3). The opposite was true in winter: November through February monthly mean precipitation and temperatures were positively correlated. In the winter, warm monthly mean temperatures are associated with a wet, maritime climate and cold temperatures come from dry, continental systems. By contrast, during the summer months, high pressure systems are typically associated with warmer, drier weather and the correlation of temperature and precipitation switches to negative (Table 1.3).

Mean monthly temperature had a strong negative relationship with snowfall at Juneau Airport and Annette Island, but not at Sitka or Yakutat, which are closer to the open ocean (Figure 1.1). Curiously, total winter precipitation (rain and snowfall) had almost no significant correlation with monthly snowfall totals (Table 1.3). These results may have been influenced by the proximity of the stations to sea level where the maritime influence caused most precipitation to fall as rain. The greatest snowfall totals typically occurred in this region during the transition from a high to low pressure system and vice versa. Therefore having a weather pattern in place that produced high totals of precipitation may not have yielded snowfall even in the coldest months of the year.

Juday (1984) noted periodicity in the climate data of Southeast Alaska ranging between 9 to 15 years. In the 1990s and 2000s an extended period of high mean annual temperatures seems to suggest a weakening of this pattern. It is possible that it is being masked by a larger warming trend in the northern Pacific Ocean (Ware and Thomson 1999, Viens 2001). The influence of ENSO is apparent in the datasets (Figures 1.2 to 1.4), especially in years of major abnormalities including 1926, 1941, and 1983 (Mantua 2002, Roden 1989, Wiles et al. 1996). PDO is clearly seen affecting the long term trends at these stations, and is especially apparent in the high values of summer mean temperatures in the late 1920s and early 1960s (Figure 1.3).

Conclusions

Several major patterns are seen across all weather stations in this study, the most notable being colder than average growing year temperature from the mid-1960s to the mid-1970s and the general upward trend in temperature in the 20th century. However, the increase in growing year temperature in southeast Alaska is modest compared to rest of Alaska (Juday 1984). Annette Island and Juneau do exhibit an increase (>1°C per century) in temperature throughout their record. All stations show a warming trend since the 1977 climate regime shift (Ware and Thomson 1999). Precipitation records do not visually suggest trends over time, nor do the levels recorded agree strongly between stations. At most stations, monthly temperature showed a significant negative relationship with precipitation during the months May through August and positive November-February, probably due to the maritime influence on the regional climate. Monthly mean temperatures also are significantly negatively correlated with snowfall at Juneau and Annette Island. Records from Southeast Alaska climate stations generally agree with larger northern Pacific Ocean trends, including ENSO and PDO.

Despite gaps in the data and changes in measurement location and techniques over time the long-term weather records and reconstructed gaps represent a useful tool for identifying general and making specific correlations in tree-ring analysis and similar studies. It is my hope that the data provided in the Appendix may be of use in future climate based analysis in Southeast Alaska and in larger scale climate comparisons.

Figures

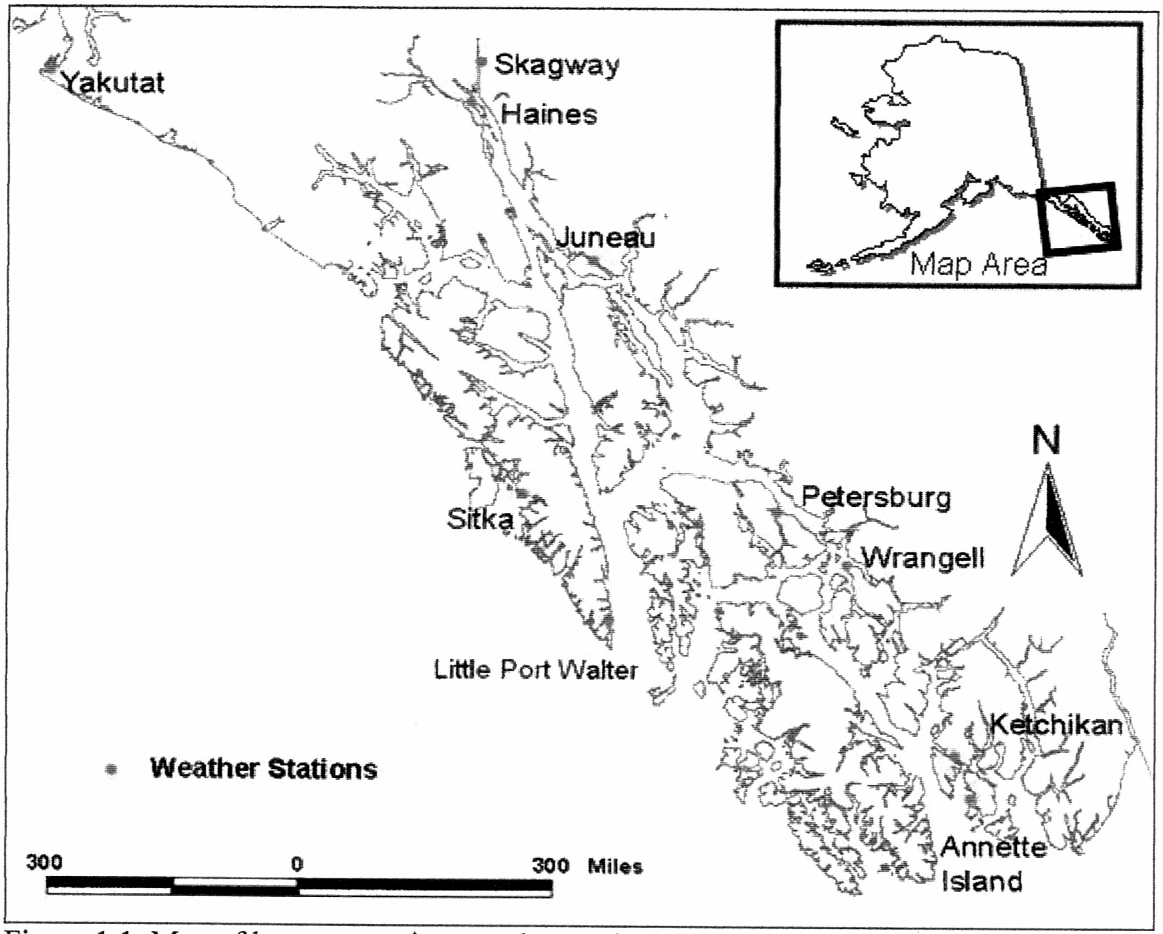

Figure 1.1. Map of longest running weather stations in Southeast Alaska.

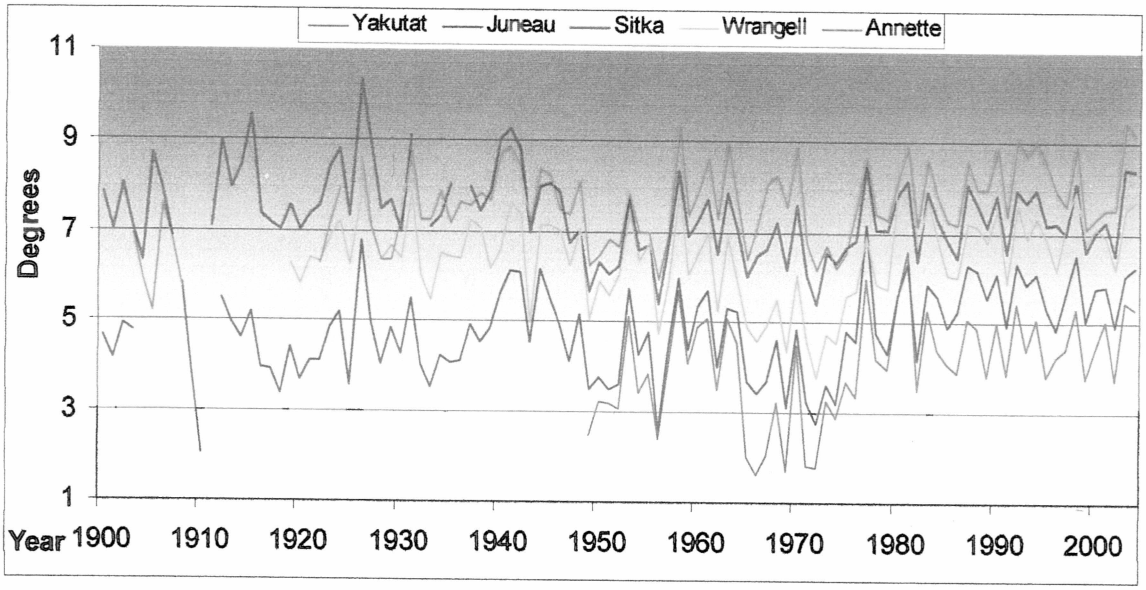

Figure 1.2. Mean annual temperature. Recorded growing year mean temperature with gaps reconstructed for five weather stations in Southeast Alaska. Growing year calculated September to August.

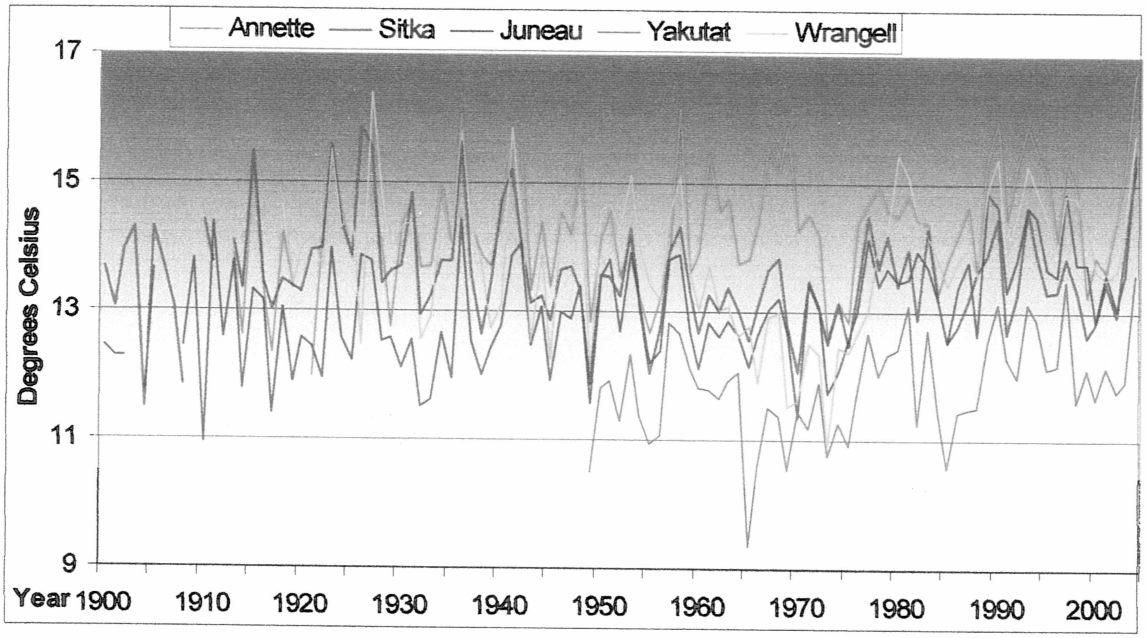

Figure 1.3. Mean summer temperature. Recorded summer mean temperature with gaps reconstructed for five weather stations in Southeast Alaska. Summer mean calculated as the average of June, July, and August monthly mean temperatures.

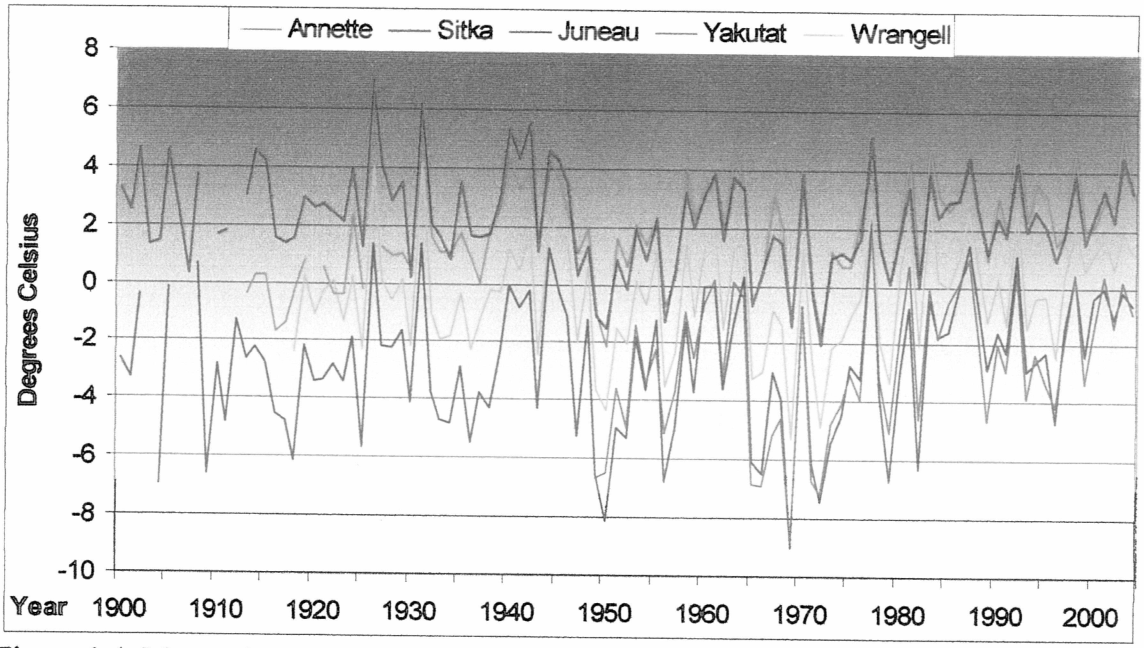

Figure 1.4. Mean winter temperature. Recorded winter mean temperature with gaps reconstructed for five weather stations in Southeast Alaska. Winter mean calculated on average of December, January, and February monthly mean temperatures.

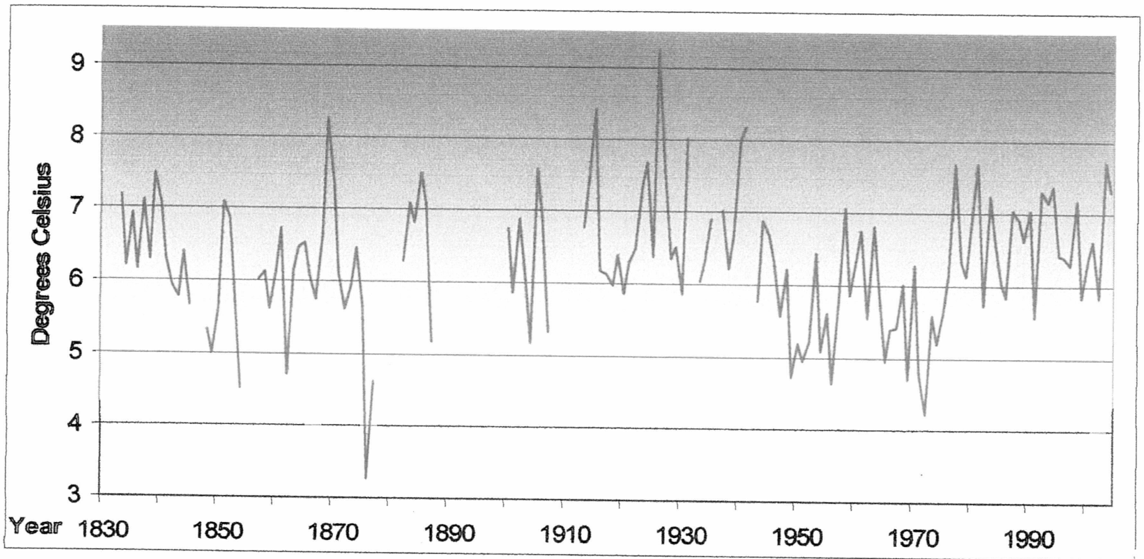

Figure 1.5. Mean annual temperature at Sitka. Recorded mean growing year temperature with gaps reconstructed at or near Sitka.. Prior to 1989 data collected at Sitka Magnetic Observatory. For 1832-1887 values, the daily mean temperatures were calculated using from 4 to 24 observations per day, and the longest period of one consistent technique was 1832 to 1845 (Roden1989). From 1899-1989, means were taken of daily maximum and minimum. Post-1989 data were recorded at Sitka Airport with gaps reconstructed.

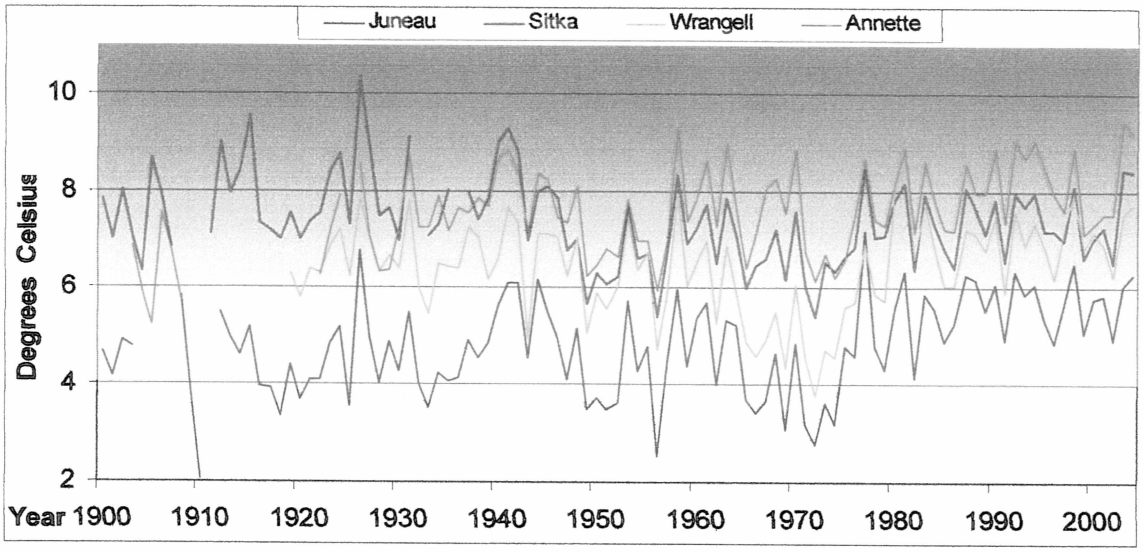

Figure 1.6. Annual total precipitation. Recorded growing year total precipitation with gaps reconstructed for four weather stations in Southeast Alaska. Growing year calculated September-August.

Tables

Table 1.1. Weather station summary for Southeast Alaska. Annual maximum temperature (AMxT), annual minimum temperature (AMnT), and annual total precipitation (ATP) based on 1971-2000 records from the Western Regional Climate Center (WRCC 2006).

Weather Station	Latitude	Longitude	AMxT (°C)	AMnT (°C)	ATP (cm)	Earliest Record	Major Gaps
Yakutat	59° 31' N	139° 40' W	7.9	0.7	405.7	1948	
Juneau Airport	58° 22' N	134° 35' W	8.7	1.9	149.1	1941	
Juneau Downtown	58° 18' N	134° 24' W	9.4	2.9	225.9	1881	1885-89, 1892-98, 1972-75
Sitka Airport	57° 04' N	135° 21' W	9.9	4.5	218.8	1944	1946-47, 1997-98
Sitka Magnetic Observatory	57° 03' N	135° 20' W	--	--	--	1828	1830-31, 1877-80, 1888-98, 1908-09, 1990-present
Petersburg	56° 49' N	132° 58' W	9.1	1.9	266.4	1926	1933-36, 1978-80, 1996-00
Wrangell	56° 29' N	132° 22' W	9.9	3.3	204.8	1917	1921-24, 1983-84, 1996
Little Port Walter	56° 23' N	134° 39' W	9.6	3.3	580.4	1936	1949, 2001
Ketchikan	55° 22' N	131° 43' W	10.7	4.2	357.9	1910	1942-47, 1978-83, 1997-98
Annette Island	55° 02' N	131° 34' W	10.8	4.8	256.6	1941	

Table 1.2. Mean growing year temperature correlations between weather stations. Growing year (September-August) temperature means compared between weather stations using Pearson correlations (significance achieved at r=0.25 to 0.40 for p=0.01 depending on length of record; all values are significant).

	Yaku -tat	Juneau AP	Juneau DT	Sitka AP	Sitka MO	Peters -burg	Wrang -ell	L.P. Walter	Ketchi -kan
Juneau AP	0.91	--	--	--	--	--	--	--	--
Juneau DT	0.81	0.89	--	--	--	--	--	--	--
Sitka AP	0.90	0.92	0.89	--	--	--	--	--	--
Sitka MO	0.90	0.95	0.73	0.96	--	--	--	--	--
Petersburg	0.88	0.94	0.88	0.93	0.95	--	--	--	--
Wrangell	0.91	0.89	0.73	0.84	0.83	0.86	--	--	--
L.P.Walter	0.92	0.94	0.85	0.97	0.95	0.94	0.85	--	--
Ketchikan	0.55	0.50	0.74	0.65	0.46	0.79	0.61	0.70	--
Annette	0.76	0.79	0.84	0.91	0.86	0.87	0.75	0.92	0.69

Table 1.3. Correlations between temperature, precipitation, and snowfall records. Pearson correlations (significance achieved at r=0.25 to 0.35 for p=0.01 depending on length of comparison) of mean monthly temperature (MMT), monthly total precipitation (MTP), and monthly snowfall total for four Southeast Alaska weather stations 1948-2004.

MMT vs. MTP	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Yakutat	0.70	0.58	0.39	0.17	0.41	0.41	0.15	0.11	0.25	0.35	0.66	0.64
Juneau	0.53	0.39	0.19	0.03	0.50	0.39	0.31	0.48	0.07	0.50	0.58	0.55
Sitka	0.49	0.29	0.11	0.13	0.50	0.57	0.28	0.34	0.29	0.19	0.53	0.41
Annette	0.57	0.25	0.01	0.24	0.50	0.58	0.46	0.45	0.30	0.08	0.40	0.57
MMT vs. Snowfall												
Yakutat	0.07	0.19	0.10	0.16	--	--	--	--	--	0.18	0.05	0.12
Juneau	0.41	0.48	0.53	0.43	--	--	--	--	--	0.47	0.52	0.56
Sitka	0.28	0.25	0.01	0.08	--	--	--	--	--	0.01	0.10	0.16
Annette	0.55	0.60	0.50	0.40	--	--	--	--	--	0.37	0.41	0.57
MTP vs. Snowfall												
Yakutat	0.07	0.19	0.10	0.16	--	--	--	--	--	0.18	0.05	0.12
Juneau	0.22	0.26	0.41	0.13	--	--	--	--	--	0.11	0.01	0.07
Sitka	0.07	0.02	0.09	0.03	--	--	--	--	--	0.00	0.22	0.28
Annette	0.08	0.10	0.35	0.14	--	--	--	--	--	0.08	0.12	0.13

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Chapter 2. Tree-ring analysis of yellow-cedar in Southeast Alaska

Abstract

Yellow-cedar is a commercially valuable tree species in Southeast Alaska, but not much is known about its tree-ring growth in the northern part of its distribution. We used a region-wide collection of tree cores to gain a better understanding of the climatic conditions favoring yellow-cedar. By comparing tree-ring measurements to climate data from four nearby stations, we found consistent, significant positive correlations between ring widths and mean monthly temperatures in August, previous January, and previous December. We found negative relationships between ring-widths and May and December precipitation. Climate indices we created explain approximately 25% of growth variability in five distinct yellow-cedar populations, and the consistency of factors included across four weather stations used suggests a real relationship between growth and climate.

Introduction

Yellow-cedar (*Chamaecyparis nootkatensis* (D.Don) Spach) is a long-lived, slow-growing tree found along the Pacific Coast from Alaska's Prince William Sound south to the Oregon-California border (Harris 1990). In Southeast Alaska it grows from sea level to timberline, typically in mixed stands with other conifers. Yellow-cedar often grows on very wet soils on the edge of muskegs where there is less canopy competition (Hennon et al. 1990a). It is a very commercially valuable tree due to its narrow-grained, clear wood which contains natural protective compounds (Harris 1990). Historically, aboriginal people utilized almost every part of the tree for a variety of purposes (Stewart 1984).

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On more than 150,000 ha throughout Southeast Alaska, yellow-cedar trees have been dying back over the past century (Hennon et al. 1990b). A biological agent has been ruled out as the cause by past research (Hennon et al. 1984, Hennon et al. 1990b). The decline is believed to be at least partly associated with muskeg expansion, though that cannot explain all of the mortality (Hennon et al. 1990a). Another possible explanation is that slightly warmer temperatures have thinned or eliminated winter snowpack in many areas. Without the insulating snow, the shallow roots have been more exposed to late-spring freezing events after dehardening, which can cause root necrosis (Bourque et al. 2005). The first published observation of widespread yellow-cedar mortality was in 1909 (Sheldon 1912), about the time a warming trend began throughout Alaska (Hamilton 1965).

In order to properly address this hypothesis of episodic events as a potential cause for decline, a background is required on what climate factors consistently drive yellow-cedar growth on an annual basis. As demonstrated in the Northeast United States in the case of yellow birch (Bourque et al. 2005), dendroclimatology can help determine the specific abiotic factors that contribute to a tree species' growth which can then be extrapolated to better explain a decline phenomenon. The scope of this paper will center on long-term patterns of climate and yellow cedar radial growth, leaving it to others to follow up and connect these findings to the current decline hypothesis.

To our knowledge, this is the first region-wide dendroclimatological study of any species conducted in Southeast Alaska. One previous published dendroclimatological study found in the region was limited to 12 mountain hemlock trees from Mitkof Island (Viens 2001). A previous dendroclimatological study involving yellow-cedar was conducted using high elevation trees on montane sites on Vancouver Island. Those yellow-cedar trees show a common growth signal and are cross-datable (Laroque and Smith 1999).

About 33% of the variation in annual ring growth in that population can be explained by climatic factors as selected by the PRECONK program (Fritts 1994) in order to maximize independent predictive component of the variables. Radial growth of montane Vancouver Island yellow-cedar was positively correlated with July air temperature and February total precipitation, and negatively correlated with August temperature, June and October precipitation in the current growing year (September to August), and August temperature of the previous growing year. This was interpreted as the trees responding positively to early snowmelt, which may increase the soil moisture reservoir and allow for an early start to the growth cycle, and a warm, dry growing season to allow for maximum photosynthesis. The trees were thought to react negatively to summer drought stress as well as incomplete hardening due to snowfall accumulation in autumn (Laroque and Smith 1999).

This study was conducted in cooperation with ongoing research on yellow-cedar ecology and the decline phenomenon conducted by the U.S. Forest Service Pacific Northwest Research Station. The objectives of this paper are to (1) determine whether there is a common growth signal among yellow-cedar trees throughout Southeast Alaska, (2) compare normalized tree ring-width series with regional climate records since the late nineteenth century, and (3) create a predictive index of annual ring-growth based on specific climate variables.

Materials and Methods

Tree Rings

We cored live yellow-cedar trees at 18 sites in Southeast Alaska from 55°N to 61°N latitude (Figure 2.1, Table 2.1). As tree cores taken in this study also were intended to provide information on declining stands, all study sites south of 58°N centered on patches of standing yellow-cedar snags. Most sites were located below 200m in elevation, within 3km of a road, and were clustered on islands with extensive logging road networks. Sampling in Peril Strait (GOOSE, POIS 1 and 2) focused on intensive Forest Service research plots (Hennon et al. 1990a) and were accessed via floatplane. At each site, we randomly selected 15 live yellow-cedar trees, representing a range of diameters and without major injury.

We took penetrating cores (bark through pith to opposite bark) at 1.37 meters above ground level at cross-slope for most trees. For larger trees two individual radial cores (bark to pith) were collected on opposite sides of the tree. Basing estimates of the annual radial growth of the tree on the average of two radial measurements dampens the effect of growth asymmetry along any single radial track and provides an opportunity to identify and account for missing rings (Cook and Kairiukstis 1992). Additional yellow-cedar tree cores and cross sectional disks were provided by the U.S.D.A. Forest Service from Prince William Sound (Hennon and Trummer 2001) and Pt. Nemo on Wrangell Island (McDonald et al. 1997). These samples were collected from all yellow-cedar within study plots (different from our random sampling) but were collected at 1.37m above ground.

In the field we mounted the cores to slotted boards and later sanded them with progressively finer-grained emery cloth, typically to 600-grit. Cores were then visually cross-dated under a dissecting microscope to check for consistency before ring-width was measured inward toward the pith to the limit of undistorted measurable rings on a Velmex sliding stage to 0.001mm resolution. To check for dating errors, we used the program COFECHA (Holmes 1983), which compares radial measurement series one at a time to the common signal in a sample, and identifies shifts in dating that would improve correlation with the master. Based on improved COFECHA correlation scores from shifts in dating, obvious dating discrepancies in the measurement series were treated as errors and corrected. The corrected files were rerun through COFECHA for final confirmation.

Neither the errors nor the corrections were independently verified. For trees with two accurately cross-dated cores, a tree-averaged ring-width series was generated. Any series suspected of containing missing rings was removed. After this step our sample size was reduced to 359 of 417 sampled trees (86% yield of measured samples).

For purposes of analysis the averaged or single ring-width series representing each tree was truncated for years prior to 1828 (the earliest weather record). The truncated raw ring-width series were then normalized and detrended using a cubic-smoothing spline with ARSTAN (Cook 1985). We used the spline to minimize the influence of (1) decreased radial growth due to age effects and geometry of growth expressed as a radial measurement (Fritts 1976) and (2) dramatic shifts in growth which likely occurred in response to canopy openings from mortality of neighboring trees in the declining stands. There is a risk of over-fitting the data and removing climatic response altogether when using this strategy. Sensitivity analysis was conducted using randomly selected trees and we found 50-years the most effective time span to fit major fluctuations without removing most ring-width variability. Initially all radial measurement series were subjected to a 50-year cubic-smoothing spline. About 30% of the population still exhibited extreme peaks in standard deviation in the normalized and detrended values. In these cases successively shorter cubic spline fits were applied down to a 25- to 35-year term, until the curves did not contain sustained periods of greater than 2.5 standard deviations.

Climate Records

The Alaska Climate Research Center (2006) in Fairbanks, Alaska provided historical data from weather stations in Southeast Alaska to 1899 at Sitka, Alaska and the early 1900s for other stations (Figure 2.1). Dr. Gunnar Roden (1989) supplied historic data from Sitka Magnetic Observatory back to 1832. We reconstructed gaps in station records to maximize continuity for the sake of comparisons to tree rings (Chapter 1). We did not do any reconstruction on Cordova weather records, which were not presented in Chapter 1. Cordova's recording station moved in 1950 from the downtown area to the airport, where its location near the Copper River canyon leads to much colder winter temperature recordings due to winds from the Interior (Lethcoe 2003). All weather stations used in our analysis are near sea level, whereas few of our sampling sites are below 100 meters elevation.

Correlation

The 359 detrended and normalized tree chronologies were averaged by region into mean ring width indices (RWI) representing Prince of Wales Island (POW), Kupreanof/ Mitkof/ Wrangell Island (INLAND), Sitka/ Poison Cove/ Goose Cove (NORTH), Cedar Bay/ Hawkins Island (PWS), and Cedar Lake (CL) (Table 2.1). The POW chronology was compared to Annette Island climate data from 1911 to 2004, INLAND and NORTH to Sitka from 1899 to 2004, PWS to Cordova from1909 to 1996, and CL to Juneau from 1899 to 2004.

We also attempted to correlate INLAND sites with nearby Wrangell and Petersburg weather station data, and PWS to Valdez, but found weak relationships possibly due to those stations' proximity to major glaciers influencing temperature data (Lethcoe 2003). The Cordova recording station had been moved from downtown to the airport in 1950, so a separate analysis was done for the pre- and post1950 series. Perhaps due to a station move in 1942, early 20th century temperature data from Sitka is on average 1°C warmer than data following the move (Juday 1984). Analysis with and without a temperature adjustment on 1899-1942 data did not differ substantially, so we used the original data to avoid introduction of additional artifacts.

We calculated Pearson correlation coefficients between regional mean RWI and the mean temperature and total precipitation for each of the 36 months prior to and including

September of the year of ring formation at each of the corresponding weather stations. We also correlated mean RWI to each of the following: growing year (September to August) mean temperature and precipitation total, growing season (May to August) mean temperature and precipitation total, and length of current and previous growing season (days between temperatures below 0°C). As these climate stations are all located at or near sea level and our coring sites were at varying elevations (Table 2.1), the growing season at the station may have little bearing on the actual experienced frost-free period in a given stand. .

Using the monthly temperature and precipitation best correlated with mean RWI, we then built a climate index (CI) where each of the four to five variables included provided significant additional predictive power. CIs were created by trial and error using mathematical combinations of climate variables normalized according to the subtraction method (Cook and Kairiukstis 1992). We started with the mean of the two highest correlated monthly records then added other highly correlated months to see if they greatly improved ($r > \sim 0.05$) the correlation with mean RWI. All variables used were weighted equally in the final equations.

Juday (1984) noted cycles in the climate data of Southeast Alaska ranging between 9 to 15 years. If favorable growing conditions continued over such an extended period of time, it is possible a yellow-cedar tree could store nutrients or increase photosynthetic capacity which may improve ring growth in following years regardless of climate. To test whether this had a cumulative effect on tree-ring growth, we also correlated smoothed yellow-cedar radial growth with smoothed climatic variables. The autoregressive properties of both times series (mean RWI and monthly weather values) usually cause an improvement in correlation after smoothing dampens short-term variability. We chose a smoothing period of about a half cycle (5 years), which enhances cycle definition length of term for the smoothing treatment. If long-term preconditioning effects are present in the growth record, the smoothed radial growth data should enhance and express it, leading to a correlation value higher than the annual comparison.

All sites were correlated to monthly mean temperature (1832-1887) and precipitation totals (1842-1887) from Sitka. Early Sitka records were taken at a small, exposed loghouse on Japonski Island (Roden 1989). The daily means were calculated using from 4 to 24 observations per day. The longest period of one consistent calculation was 1832 to 1845 when four daily observations were averaged. The only data available from NOAA (either taken by American observers or records in American custody from Russian sources) for this period are monthly means. Given these limitations, the 19th century Sitka data were correlated and interpreted separately.

Once the regional climate index that best modeled the growth of the five regional samples was developed, a regression of climate index versus ring-width index was performed. Regressions were developed for three time periods: (1) the entire period of overlap of the climate station and mean RWI, (2) the period of climate data and mean RWI overlap through 1949, and (3) the period of overlap from 1950 through 2004.

Results

The yellow-cedar trees from POW, INLAND, and NORTH all showed a common growth signal (Table 2.3), although there were discrepancies between regions. Suppressed marker rings common to all three regions included 1878, 1887, 1904, 1944, and 1987 (Figures 2.4-2.8). Large marker rings in the 3 regions included 1892, 1927, 1932, 1941, 1962, and 2004. The geographically distant population of PWS trees showed some unique marker rings, such as large rings in 1900 and 1983, and suppressed rings in 1842, 1916, and 1971(Figure 2.8). The mean RWI from all five regions showed a very distinctive lull in growth 1954-1959, followed by a growth spike 1962-1968 (Figures 2.4-2.8).

The long-term climate records from Annette Island, Sitka, Juneau, and Cordova are variable in average temperature and total precipitation experienced (Table 2.2). Temperature values tend to show more consistency between stations than precipitation totals (Table 2.4). Years of anomalously high and low mean monthly temperatures are similar among the stations (Figure 2.2, Figure 2.3). High monthly mean temperatures are especially noticeable in the winters of 1926, 1931, and 1977. Low means are consistent across the stations in 1950, 1969, and 1996 (Figure 2.2). August means were high across the four stations in 1923, 1936, 1977, and 2004 and consistently low in 1928, 1973, and 1985 (Figure 2.3). One of the most characteristic features in the climate records is the below average winter temperatures between 1964-1975 (Figure 2.2).

The Pearson correlations between mean RWI and monthly mean temperature were typically positive relationships, but some of the highest correlation scores with monthly total precipitation were negative (Figure 2.4). The strongest, most consistent variables (significance achieved at $r > 0.25$ for $p = 0.01$) were a positive growth response to warmer August temperatures of the growing season in which the ring was formed, warmer winter monthly mean temperatures from the year prior to ring formation, and less precipitation in December immediately prior to growth. At all sites radial growth was positively correlated with temperature and negatively correlated with precipitation in April and May of the growing year, although the correlations were not always significant (at $p < 0.01$). Growing season length and mid-summer monthly variables had consistently nonsignificant correlations, even at low confidence levels ($p > 0.10$)

The specific predictive indices developed for each region are similar in the set of months combined into the index and the level of correlation (Table 2.5). The correlation with climate index (CI) is stronger for the mean RWI ($r = \sim 0.50$) than 98% of individual tree chronologies (median =~0.10). The CI developed for Cedar Lake (CL) mean RWI has the lowest correlation of all sites (Table 2.5), except for the period 1975-2004. In the other four regions correlation appears stronger in the period pre-1950 than post-1950, although there were fewer cases compared in the earlier period. Previous January temperature represents the month with the highest individual predictive power ($r>0.50$) before 1950, but is not nearly as strong in more modern periods (typically $r > 0.20$).

As seen in Figure 2.5-Figure 2.9, there is general point to point congruence between the mean RWI and CI, especially from 1910-1960 and 1990-2004. The largest discrepancies between CI and mean RWI occur across the region during most of the 1960s and in 1986-87. There is poorer linear predictive power from 1950-2004 (Figures 2.5-2.9) as compared to the pre-1950 time period where there are typically fewer cases.

Correlation scores of mean RWI and CI smoothed as five-year running means were lower than unsmoothed annual data. The transformation of the data using a five-year running mean causes mean RWI datasets to almost resemble a straight line, while enhancing the apparent cyclical nature of the CI values.

Monthly mean temperature and precipitation correlations with historical Sitka records from 1832-1887 returned some significant results (significance achieved at $r>0.30$ for $p=0.01$ for the number of cases of comparison) which were consistent when compared across the five regional mean RWI. The highest positive correlations were found with April, November, previous January temperature, and previous July precipitation. Correlations with October precipitation of the growing year in which the tree-rings formed were strongly negative ($r<-0.40$). Both September temperature and precipitation totals were negatively correlated with mean RWI across all regions.

Discussion

Typically in dendroclimatological analysis there are some trees that are excellent responders to climate variables and some that for a variety of factors are not (Cook and Kairiukstis 1992). Our analysis suggests relatively poor climate correlations for all individual trees even after detrending. However, when we averaged the normalized and detrended tree ring measurements into regional ring width indices (mean RWI) the correlation scores (r=~0.50) were much higher than all but approximately 2% of individual tree chronologies. This is likely due to the ability of yellow-cedar to survive for centuries at very low rates of radial growth (Hennon et al. 1990a), then quickly increase in growth especially when growth resources become available from the death of neighboring trees. Given that our samples were taken from decline stands with many snags, it is likely that the canopy opened dramatically for most of the sample trees over the past century, potentially releasing nutrients or other growth-promoting factors in addition to increasing light available to surviving trees.

After averaging between 74 and 105 trees' RWI into each of the four regions' mean RWI, the growth spikes that remained after detrending were decreased by other trees' moderate or negative responses to the same events. This combination diminished the effect of growth bias of individual trees and created a dataset that more closely matched the climate variables. However some regional, non-climatic growth-response remains. Our results provide a basis for identifying the possible years in which additional studies might focus in order to identify the factors responsible for accelerated yellow-cedar mortality specific to the regions studied. It remains to be determined whether the survivor trees sampled are genetically different than the trees that died or whether they were simply growing on more favorable microsites. We have observed very healthy yellow-cedar growing on elevated areas of soil and down woody debris adjacent to dead and declining trees that are rooted in muskeg.

The climate of Southeast Alaska is heavily influenced by the presence of maritime, low pressure and continental, high pressure weather systems (Chapter 1). The effects can be hidden by using monthly climate variables, but typically continental weather patterns are associated with drier conditions and greater temperature fluctuations, making winter months colder and summer months warmer. In Figure 2.4, the positive correlation of yellow-cedar radial growth with temperature but negative relationship with precipitation in July and August is consistent with the trees taking advantage of decreased cloudiness under high pressure. The positive correlations of temperature and precipitation with yellow-cedar growth in October through January is apparently indicative of a favorable effect of maritime conditions. The mean RWI correlations with climate variables were likely to be strongly influenced by the distinctive lull in growth 1954-1959 and the growth spike 1962-1968 (Figures 2.4-2.8).

The climate indices we created suggest the most ecologically important variables to yellow-cedar diameter growth. The most dominant and consistent monthly climate variables occurred in winter, especially the winter of the year previous to ring formation. This suggests that yellow-cedar trees, like many conifers, are partially determinant growers (Cook and Kairiukstis 1992). Carroll and Jules (2005) reported similar positive correlations with winter temperature in populations of Port Orford cedar in the Siskiyou Mountains of Oregon. In addition, their population responded positively to winter precipitation, but our yellow-cedar showed the opposite response, especially to December precipitation of the current growing year. Little et al. (1995) found a similar negative correlation in Douglas-fir in the Siskiyou Mountains.

The high correlations of radial growth and winter temperatures may simply be an artifact of winter temperature being the best indicator of growing year conditions because the atmospheric pressure is the most stable at that time of year (Roden 1989). Thus the trees may not be responding directly to winter conditions, but using monthly variables the winter months give the clearest picture of overriding climate conditions. This may especially be true in the Pacific Coast of North America where weather patterns are heavily influenced by El Niño-Southern Oscillation (ENSO) and Pacific Decal

Oscillation (PDO) (Roden 1989, Wiles *et al.* 1996, Ware and Thomson 1999). Notable marker rings in our yellow-cedar samples often occurred in El Niño (1941 and 1987) and La Niña years (1904, 1932, and 1944).
It is also possible that warm winters could allow yellow-cedar to photosynthesize at a reduced capacity (Emmingham and Waring 1977) or that especially cold winter conditions could injure insufficiently hardened cells (Bourque *et al.* 2005). The decrease in predictive power since 1950 of previous January mean temperature may represent a change in that months' typical weather pattern over time. December has retained and in some instances improved its correlation over that same time period. This may signify a change in mean temperature or increase in atmospheric disturbance in January, which obfuscates the signal it used to have in common with ring formation. The change since the 1950s may be indicative of changes in stand dynamics as cedar decline increased following this time period (D'Amore and Hennon 2006).

The lack of strong correlation with summer mean temperature and precipitation, as well as growing season length, is intriguing. It suggests that summer climate variables may not vary widely, or that the extremes seen in the region have a ceiling that remains within yellow-cedar's range of adaptability without impacting diameter growth. Given the wet soils that typically support yellow-cedar in Southeast Alaska, it is not surprising that its growth does not respond to drought stress. It shows an affinity for decreased precipitation and warmer temperatures in April in May, which may signify a relationship between those variables and an early start to the growing season or an increased photosynthetic capacity under clear skies. The fact that growing season length was not a good indicator is not surprising, given the geographic complexity of the region and the influence on weather patterns. Also, the weather stations are all near sea level and most of our samples were taken from higher elevation where growing season may have been markedly shorter or more inconsistent in length than at the weather stations.

August temperature had a significant positive correlation with all mean RWI (Figure 2.4). It also shows unique predictive ability with no significant autocorrelation with other monthly variables (other than July). This could indicate that warm or sunny days in this month may delay the onset of hardening in yellow-cedar trees. Growing season in the study area often stretches into November based on a 0°C freeze event definition, but it is unlikely that the trees wait for that cue to develop freeze tolerance given the poor correlations from September onward. The montane yellow-cedar from Vancouver Island used by Laroque and Smith (1999) show a significant negative response to August temperature, and none of their strongest monthly indicators were significant growth predictors for Southeast Alaska yellow-cedar. Despite the regional similarities, the two samples were from very distinct growing sites, with our samples relatively close to sea level and all their trees collected above 1180m elevation.

Overall, climate index (CI) shows strong point to point congruence with mean RWI (Figures 2.5-2.9). The most glaring and long-lasting divergence occurs in the 1960s, where CI underestimates growth. This could partially be a result of growth release from a major stand dieback and decline in the 1950s. There is evidence of a black-headed budworm outbreak from 1952-55 (Mask 1992) which appears to have reduced competition from trees that compete with yellow-cedar, especially mountain and western hemlocks. The other major deviation between CI prediction and growth was an overestimate of growth 1986-87, during a major ENSO event. Given the large distribution of those two years as poor growth rings, it is possible that a single, region-wide springtime frost could have injured all trees in 1986. It is the divergence in the 1960s and 1987 time periods which account for most of the outliers in the linear regressions (Figures 2.5-2.9) and cause the Pearson correlation to not achieve pre-1950 levels (Table 2.5).

Considering the gaps and multiple calculations used in the early Sitka monthly weather records (Roden 1989) it is somewhat surprising that we found any significant correlation of this climate record with yellow-cedar radial growth. The predominance of autumn month variables at Sitka with strong correlations to mean RWI during the nineteenth century is markedly different than the null values we found post-1900. The only month that correlates strongly in both time periods is previous January temperature, which itself has decreased in predictive power since 1950. It suggests that yellow-cedar trees may be responding to different climate factors over time, which would make it inadvisable to reconstruct past weather patterns from their tree-rings. Possibly, the monthly values most representative of larger climate patterns like ENSO vary over time and the trees are still responding to those. The correlations may simply be a function of the fewer data points ($n=\sim45$ per correlation, significance reached at $r=\sim0.35$ for $p=0.01$) or false positives due to the various daily average temperature calculations over time.

Conclusions

Yellow-cedar trees in Southeast Alaska share a common growth signal that is also similar to trees found at the northern limits of its distribution in Prince William Sound. Their growth patterns are different than yellow-cedar growing at high elevations on Vancouver Island and Port Orford cedar from Oregon (Laroque and Smith 1999, Carrol and Jules 2005). Yellow-cedar in Southeast Alaska also respond to different monthly climate indicators than these related populations to the south. The most consistent, significant correlations occur in winter months, which may be the strongest indicator of larger weather patterns dominating the Pacific Ocean (Roden 1989). August temperature has a positive relationship with growth, probably due to a lengthening of growing season as the trees are growing latewood (Laroque and Smith 1999).

Climate indices we created explain approximately 25% of growth variability in five distinct yellow-cedar populations. Although created from four separate weather station datasets, there is consistency in the monthly variables used (Table 2.5), which suggests the interactions of the variables may elicit a consistent physiological response in the trees. The climate indices may have limited application predicting yellow-cedar growth in the future without having to sample trees in the field.

Now that we have created a regional tree-ring chronology and have formatted the weather station data in the area, it would be easier and very interesting to compare climate correlations from other tree species in the region. Finally the fact that yellow-cedar in Southeast Alaska are cross-datable and very long-lived could allow for a climate reconstruction at low elevations in Southeast Alaska centuries prior to recorded data.

Future articles employing this dataset by authors Colin Beier, Paul Hennon, and Dave D'Amore will discuss the spring freeze injury hypothesis as a driver of yellow-cedar decline.

Figures

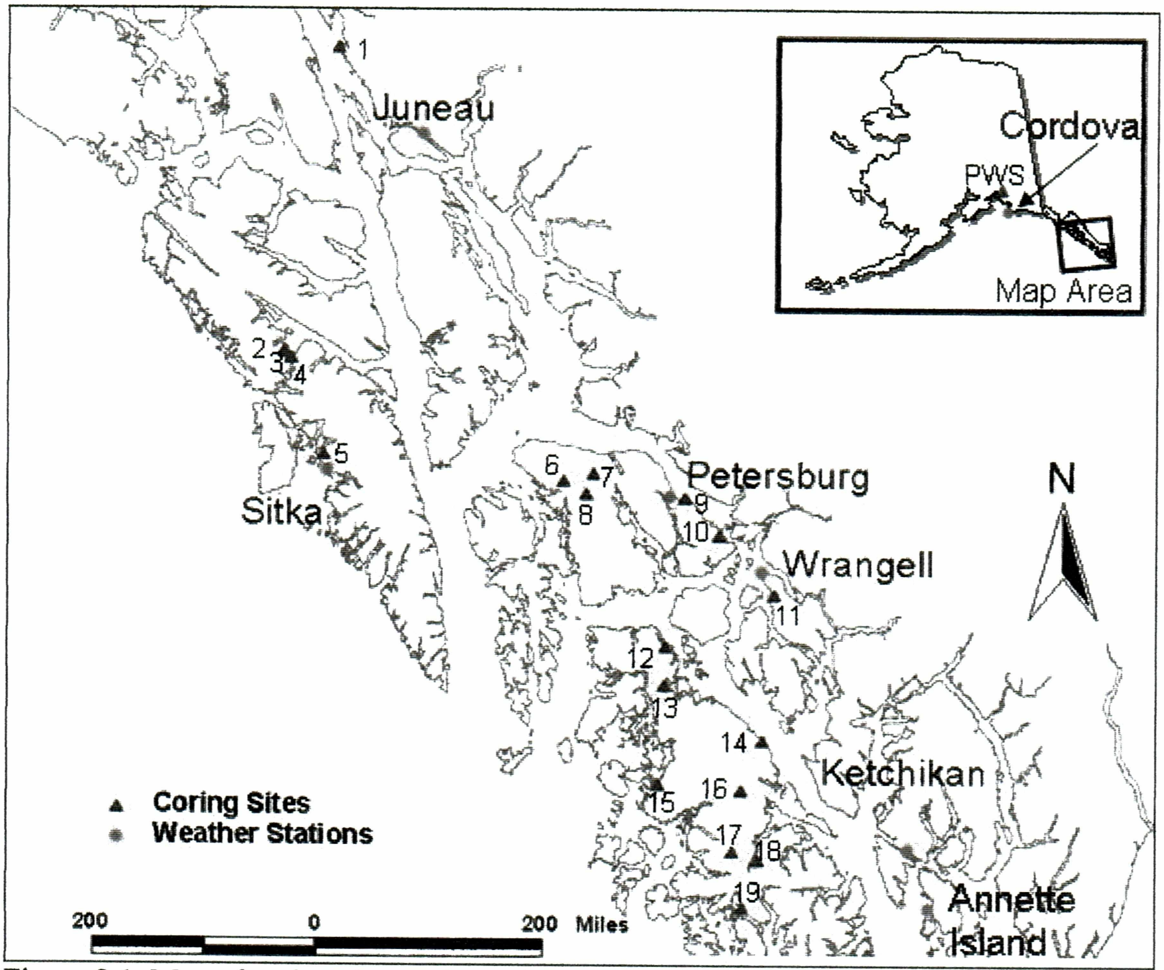


Figure 2.1. Map of coring sites and weather stations in Southeast Alaska.

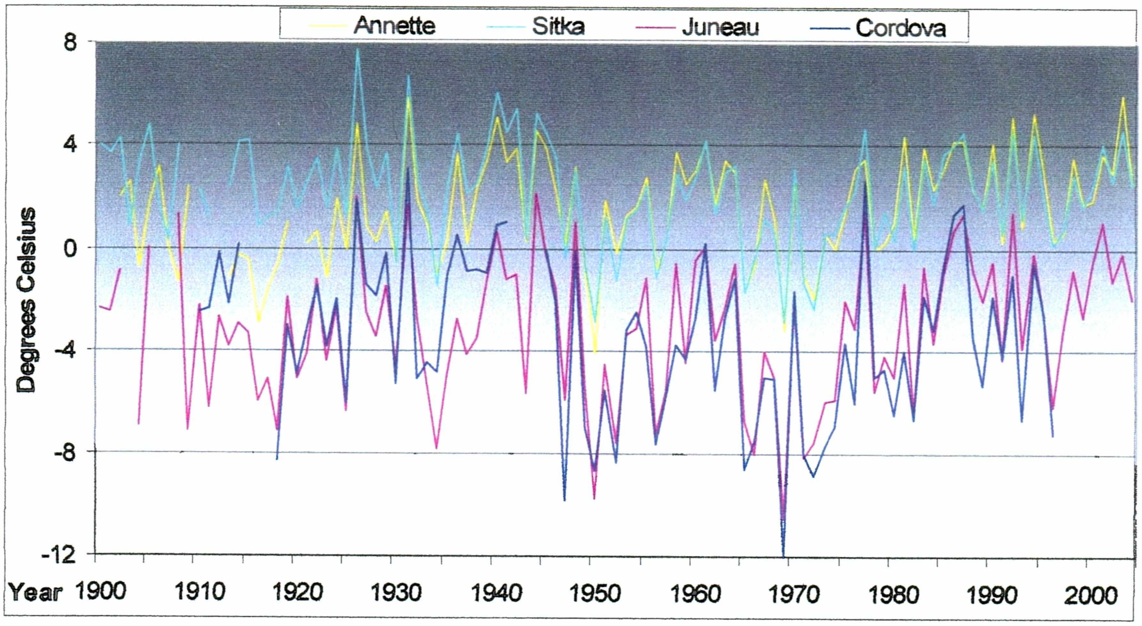


Figure 2.2. Mean winter temperature. Recorded mean winter temperature at four Alaska climate stations with data gaps reconstructed. Winter temperature based on average of January and December and graphed at January year.

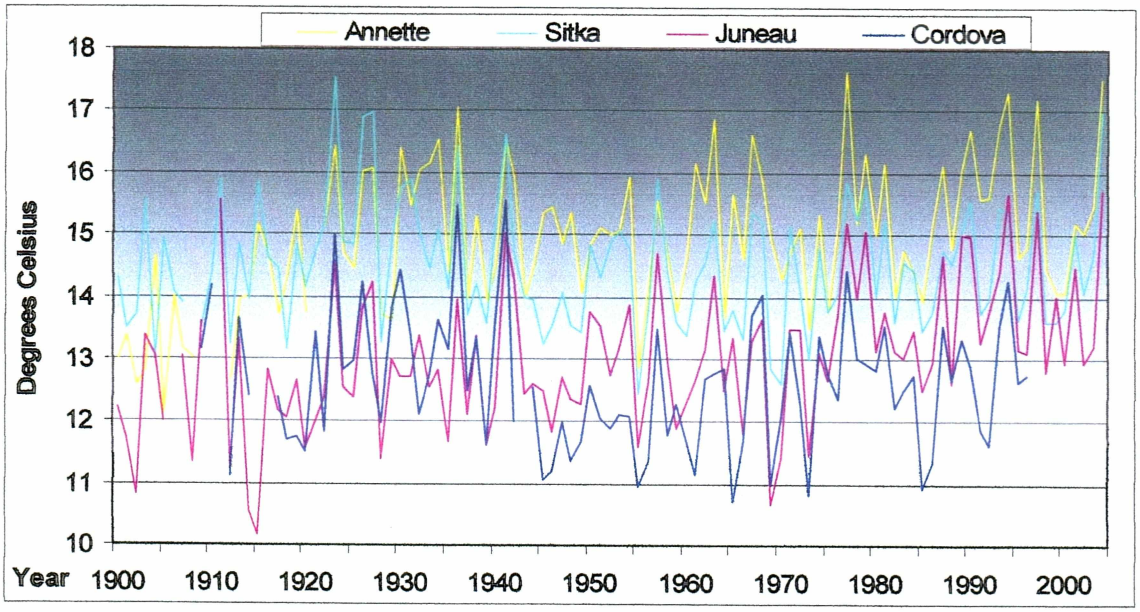
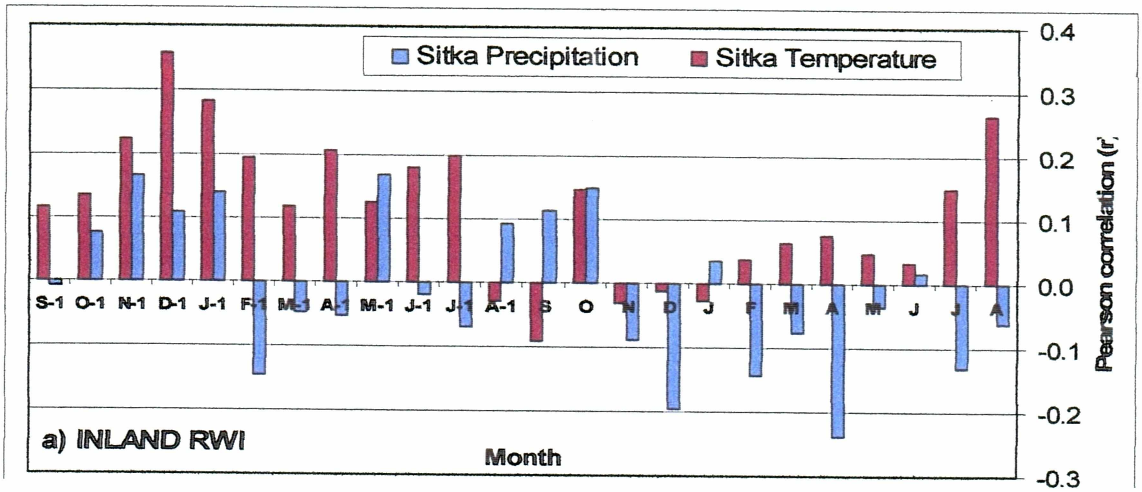


Figure 2.3. Mean August temperature. Recorded mean August temperature with data gaps reconstructed at four Alaska climate stations.



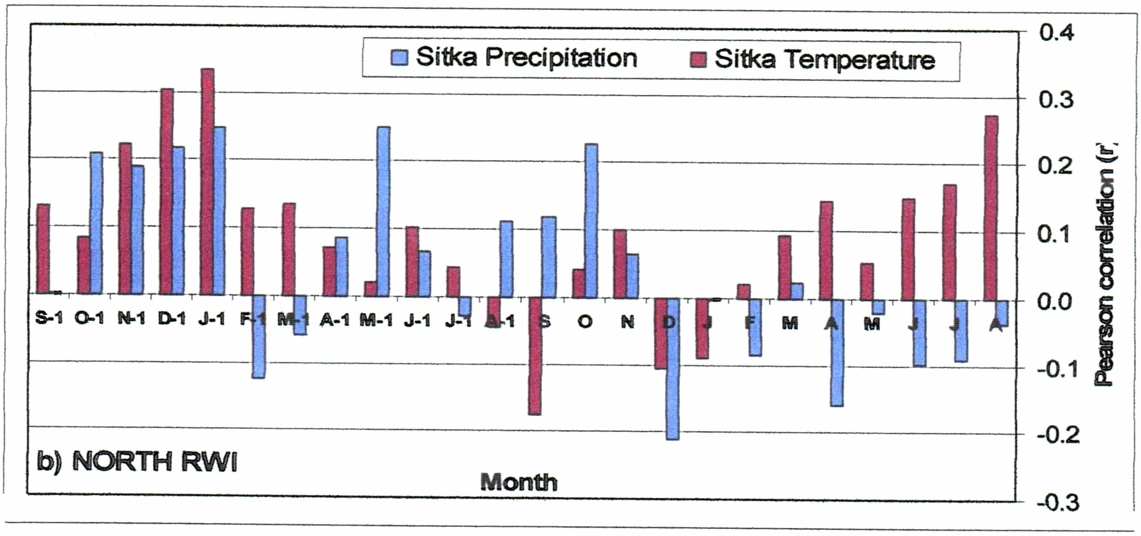
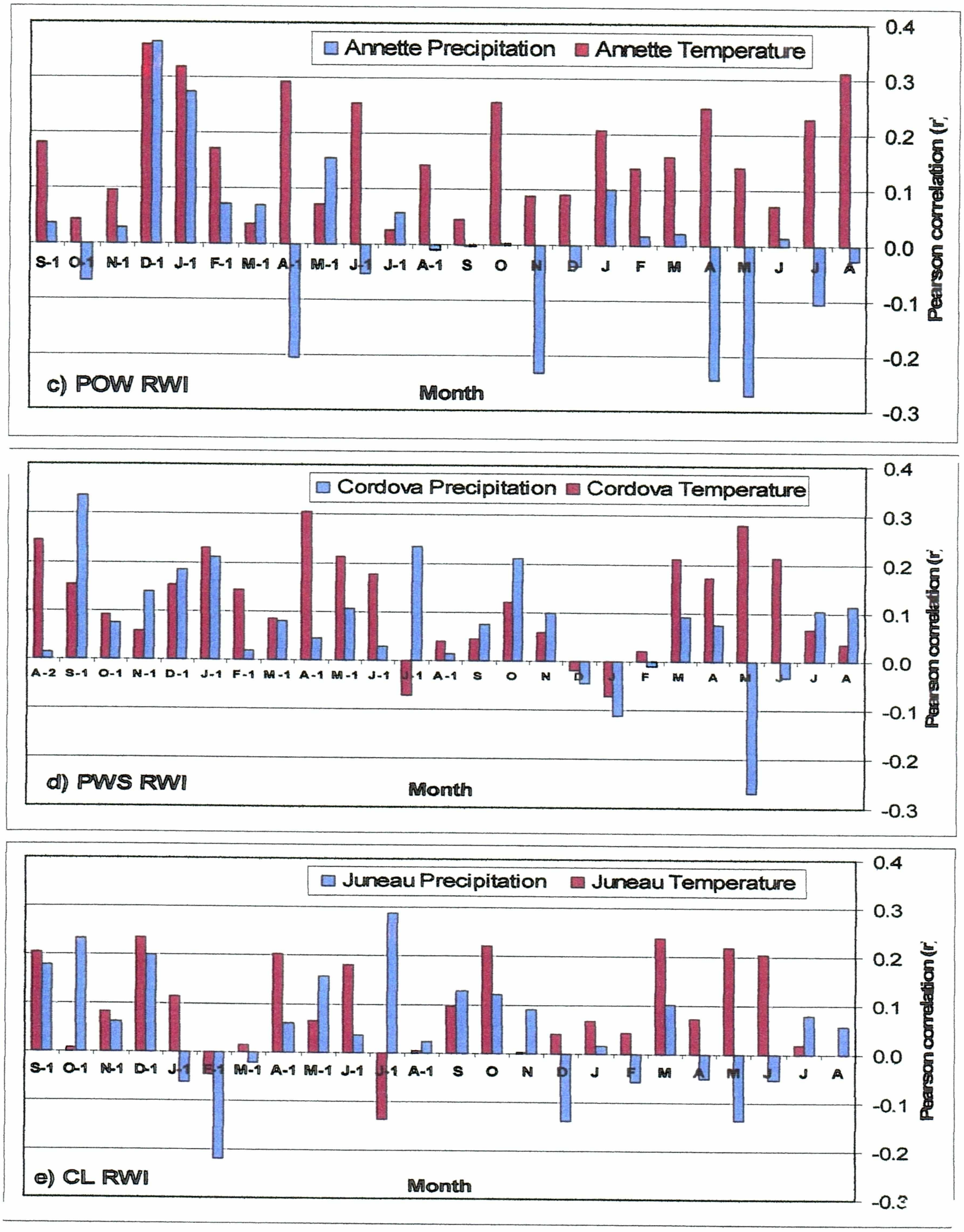


Figure 2.4. Correlation scores for each region. Correlation between mean ring width index and monthly climate variables. Significance achieved at r>0.25 for p=0.01. Months listed in chronological order from oldest to most recent, "-1" representing the year prior to ring formation.

Figure 2.4 continued



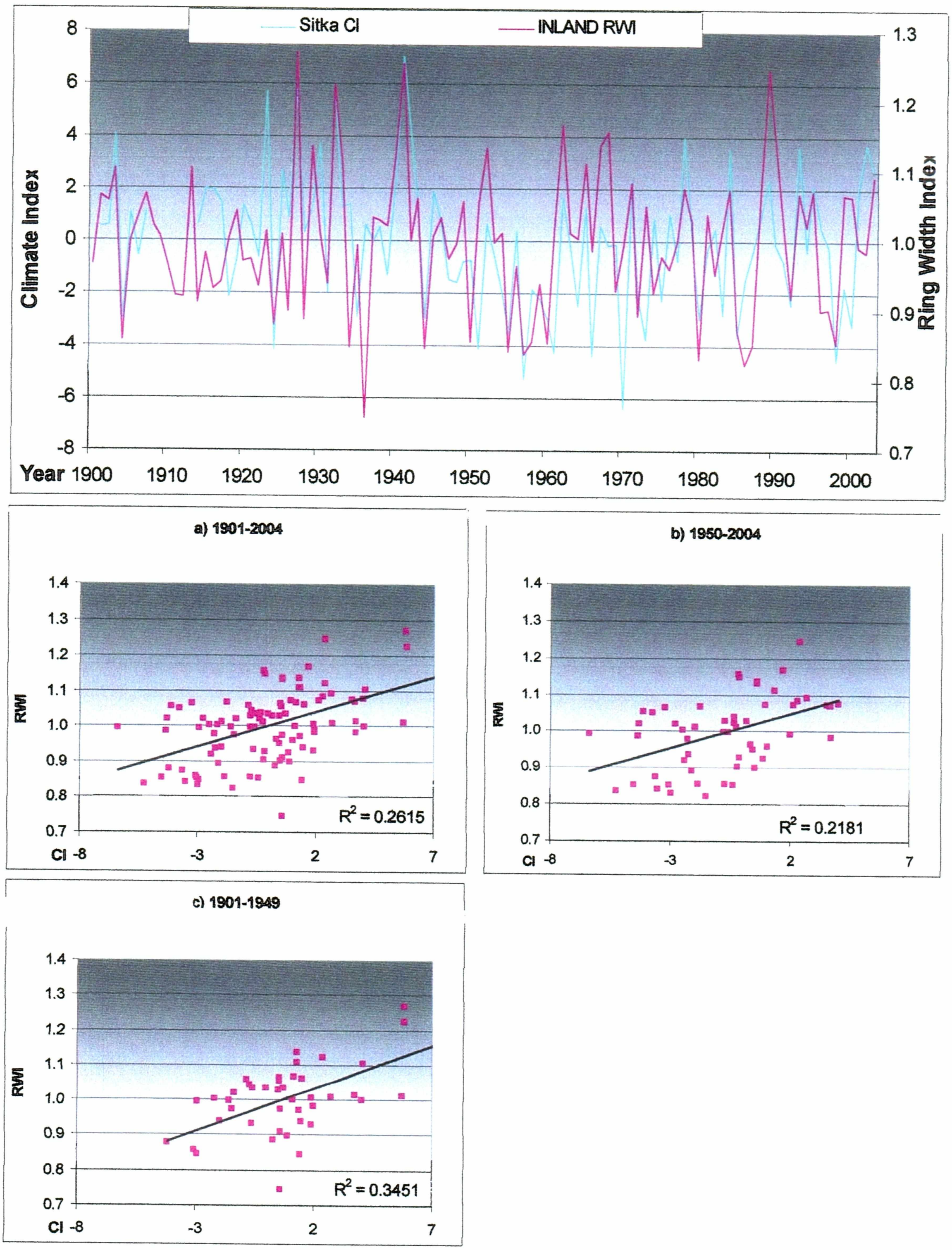


Figure 2.5. CI vs. RWI—INLAND. Climate index developed for INLAND yellow-cedar trees in Southeast Alaska.

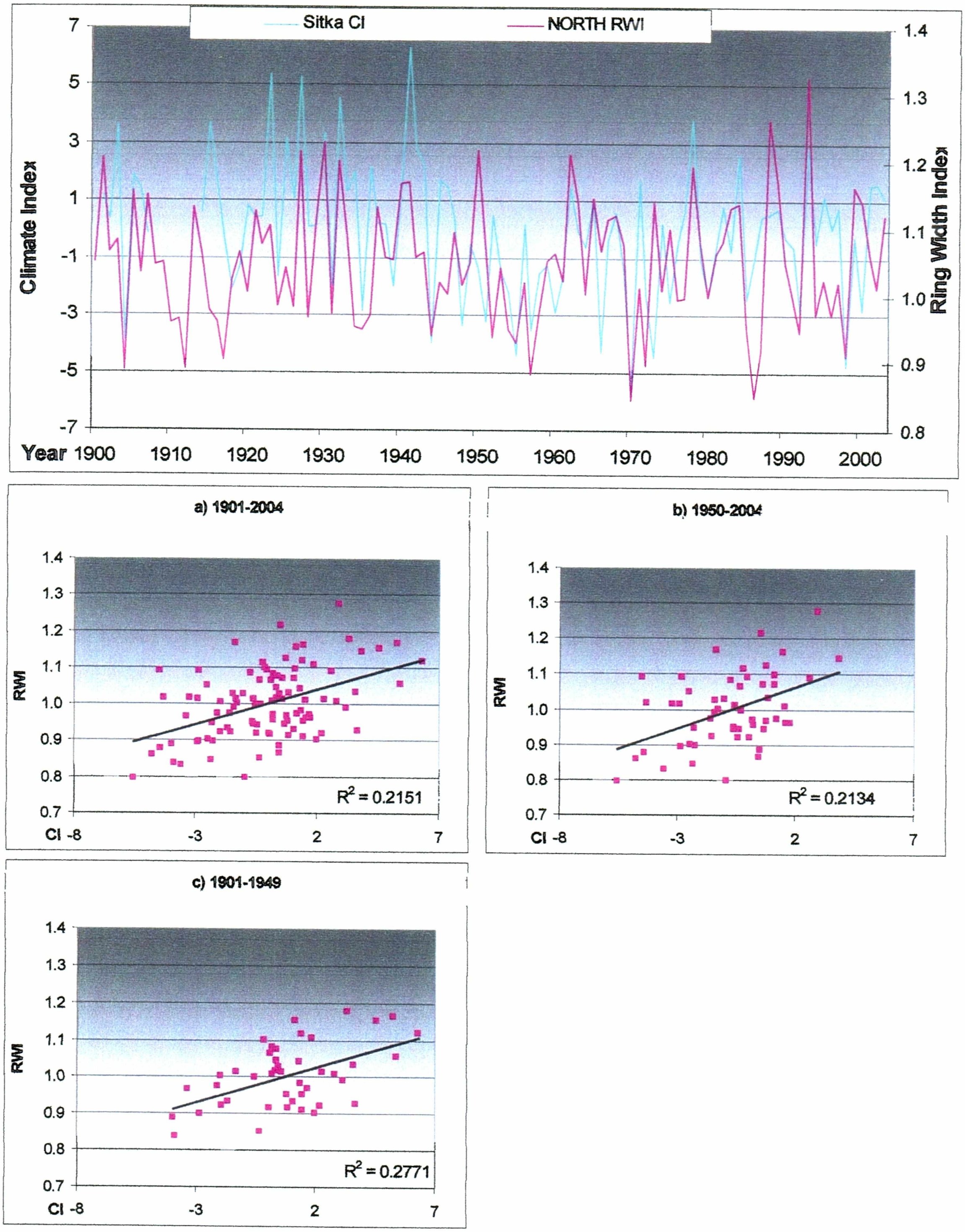


Figure 2.6. CI vs. RWI—NORTH. Climate index developed for NORTH yellow-cedar trees in Southeast Alaska.

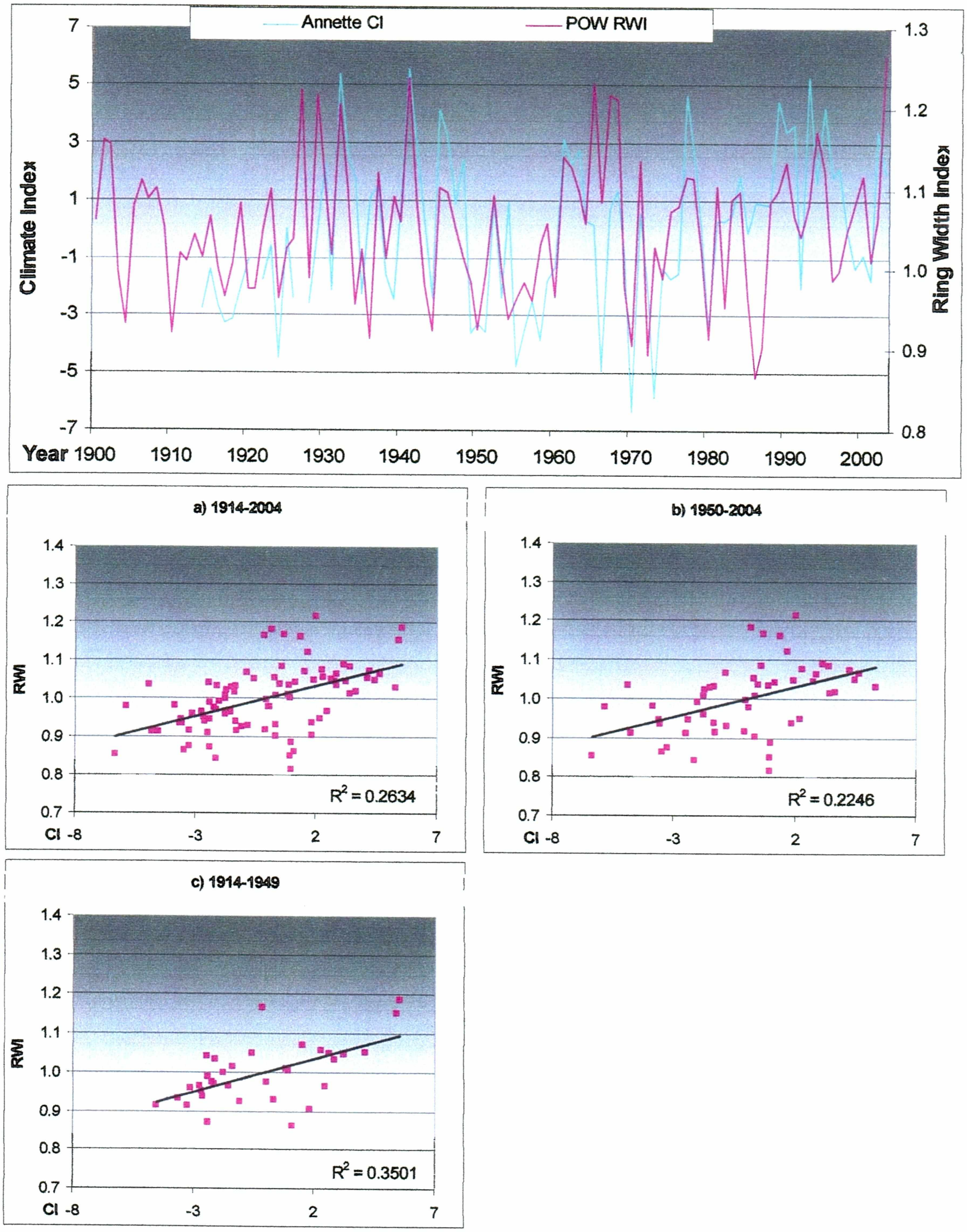


Figure 2.7. CI vs. RWI—POW. Climate index developed for Prince of Wales yellow-cedar trees in Southeast Alaska.

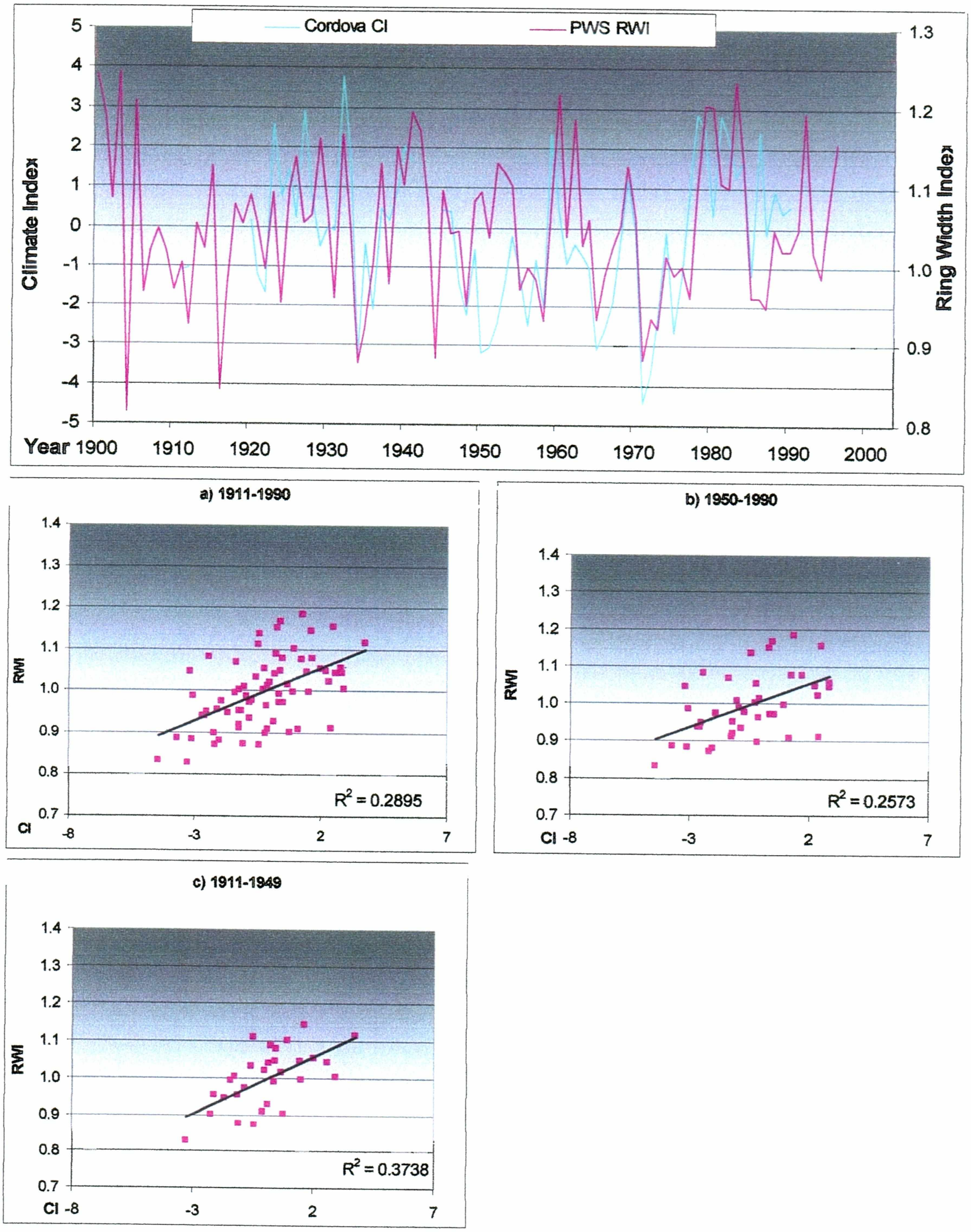
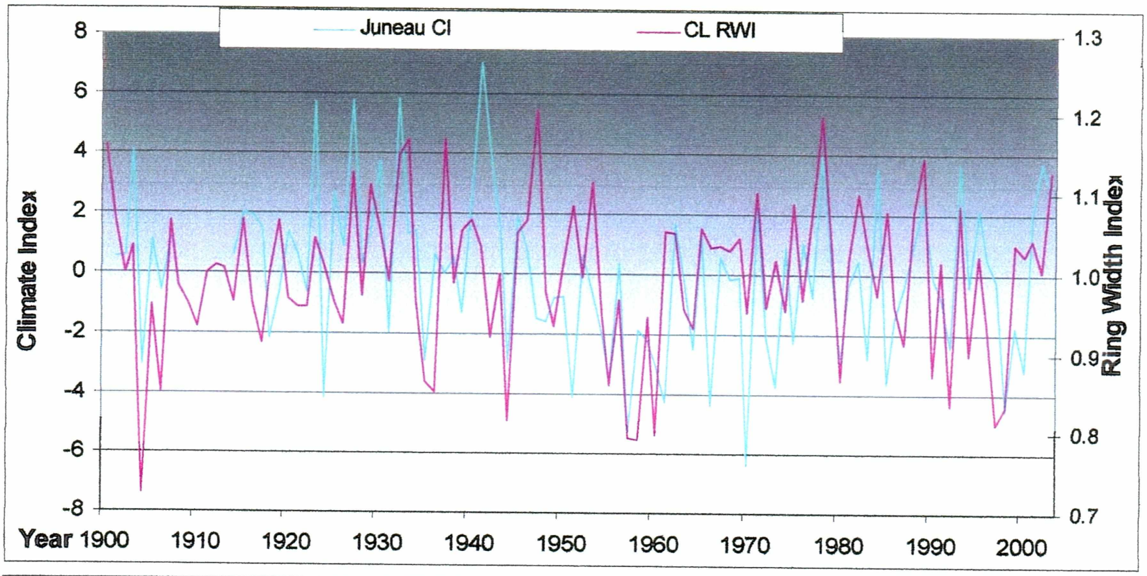
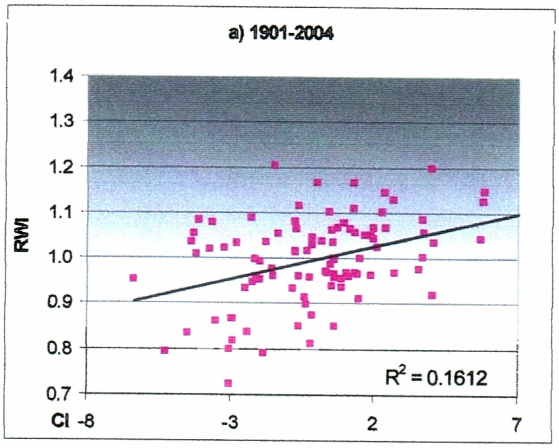
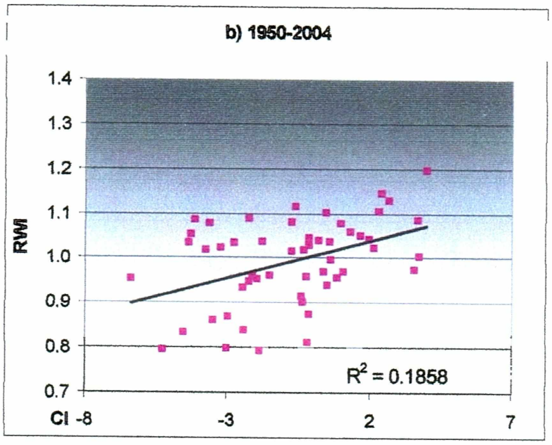


Figure 2.8. CI vs. RWI—PWS. Climate index developed for Prince William Sound yellow-cedar trees.







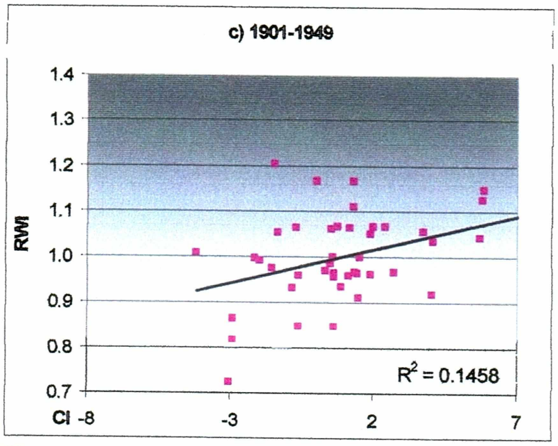


Figure 2.9. CI vs. RWI—CL. Climate index developed for Cedar Lake yellow-cedar trees north of Juneau, Alaska.

Tables

Table 2.1. Coring site summary. Location and characteristics of yellow-cedar coring sites in Southeast Alaska. Diameter at breast height (DBH) based on mean of all trees cored with a range of all diameters in parentheses. Trees cross-dated shows the number of trees successfully cross-dated from each site that went into the final regional groupings (totals in bold). Samples from a notable cedar decline stand marked with "X."

Map	Site	Latitude	Longitude	Average DBH (cm)	Trees	Decline Stand
	PWS				**105**	
PWS	CB 2	60° 57' 59.10" N	147° 23' 14.76" W	(13-61)	24	
PWS	CB 1	60° 56' 42.85" N	147° 24' 48.82" W	(20-76)	26	
PWS	HI 2	60° 34' 22.03" N	145° 57' 06.12" W	(17-72)	23	
PWS	HI 1	60° 34' 09.66" N	145° 57' 15.13" W	(18-44)	32	
1	**CL**	58° 39' 58.14" N	134° 58' 05.37" W	27.9 (16-48)	**14**	
	NORTH				**76**	
2	POIS 2	57° 31' 49.53" N	135° 34' 59.92" W	35.2 (16-80)	16	X
3	POIS 1	57° 31' 33.58" N	135° 34' 40.85" W	34.7 (13-65)	23	X
4	GOOSE	57° 30' 14.82" N	135° 32' 19.02" W	34.7 (15-61)	22	X
5	SITKA	57° 07' 34.87" N	135° 21' 52.00" W	28.8 (17-53)	15	X
	INLAND				**74**	
6	NKUP 1	56° 56' 14.92" N	133° 28' 16.18" W	28.8 (13-79)	6	X
7	NKUP 2	56° 55' 18.31" N	133° 41' 21.09" W	25.4 (15-34)	14	X
8	NKUP 3	56° 51' 41.16" N	133° 32' 20.66" W	33.6 (10-58)	12	X
9	MIT 1	56° 47' 40.98" N	132° 51' 14.32" W	36.6 (21-65)	15	X
10	MIT 2	56° 38' 06.23" N	132° 38' 52.89" W	36.3 (21-70)	15	
11	NEMO	56° 17' N	--	--	12	
	POW				**90**	
12	NPOW 5	56° 14' 21.38" N	133° 06' 48.53" W	34.6 (14-86)	13	X
13	NPOW 1	56° 05' 35.95" N	133° 09' 39.68" W	31.1 (14-91)	15	X
14	NPOW 4	55° 49' 55.77" N	132° 31' 48.88" W	31.9 (15-51)	8	X
15	NPOW 2	55° 43' 07.64" N	133° 17' 11.75" W	29.8 (8-82)	11	X
16	NPOW 3	55° 39' 21.15" N	132° 43' 14.90" W	25.2 (12-51)	10	X
17	SPOW 1	55° 25' 45.42" N	132° 50' 14.92" W	33.9 (16-73)	11	X
18	SPOW 2	55° 23' 09.24" N	132° 40' 07.47" W	22.4 (12-47)	11	X
19	SPOW 3	55° 12' 49.90" N	132° 49' 09.06" W	36.0 (16-79)	11	X

Table 2.2. Weather station summary for Southeast Alaska. Annual maximum temperature (AMxT), annual minimum temperature (AMnT), and annual total precipitation (ATP) based on 1971-2000 records borrowed from the Western Regional Climate Center (WRCC 2006).

Weather Station	Latitude	Longitude	AMxT (°C)	AMnT (°C)	ATP (cm)	Earliest Record
Valdez	61° 07' N	146° 16' W	6.9	-1.8	152.5	1917
Cordova	60° 30' N	145° 30' W	8.6	3.0	403.2	1908
Yakutat	59° 31' N	139° 40' W	7.9	0.7	405.7	1948
Juneau Airport	58° 22' N	134° 35' W	8.7	1.9	149.1	1941
Juneau Downtown	58° 18' N	134° 24' W	9.4	2.9	225.9	1881
Sitka Airport	57° 04' N	135° 21' W	9.9	4.5	218.8	1944
Sitka Magnetic Observatory	57° 03' N	135° 20' W	--	--	--	1828
Petersburg	56° 49' N	132° 58' W	9.1	1.9	266.4	1926
Wrangell	56° 29' N	132° 22' W	9.9	3.3	204.8	1917
Little Port Walter	56° 23' N	134° 39' W	9.6	3.3	580.4	1936
Ketchikan	55° 22' N	131° 43' W	10.7	4.2	357.9	1910
Annette Island	55° 02' N	131° 34' W	10.8	4.8	256.6	1941

Table 2.3. Correlation of regional ring width chronologies. Pearson correlations (significant at r=>0.01) of ring width chronologies from five regions of Alaska for 1828-2004, except Prince William Sound (PWS) 1828-1996.

	INLAND	NORTH	POW	PWS
NORTH	0.64	--	--	--
POW	0.72	0.56	--	--
PWS	0.34	0.45	0.33	--
CL	0.51	0.50	0.42	0.36

Table 2.4. Correlation of reconstructed Alaska weather station records. Pearson correlations (significant at r=>0.01) of reconstructed weather station records from 1900-2004 for mean temperature and precipitation total of growing year (September-August).

Temperature	Cordova	Juneau	Sitka
Juneau	0.67	--	--
Sitka	0.91	0.71	--
Annette	0.58	0.67	0.57

Precipitation	Cordova	Juneau	Sitka
Juneau	0.06	--	--
Sitka	0.14	0.63	--
Annette	-0.10	0.25	0.39

Table 2.5. Correlations of climate indices developed for each regional ring width index. Pearson correlations (significance achieved at r=0.25-0.40 for p=0.01 depending upon number of cases) shown for variable time periods 1900-2004 (Correlation), 1900-1949 (pre1949), 1950-2004 (post1950), and 1975-2004 (post1975). Climate Index for INLAND and NORTH based on reconstructed monthly means from Sitka, POW from Annette Island, PWS from Cordova, and CL from Juneau, Alaska. Climate Index months followed by a "T" are temperature variables and "P" are precipitation, preceded by "p" signify a month from the previous growing year to ring formation, "pp" means two years previous, "+" symbolizes a positive relationship with RWI and "-" negative.

RWI	**Climate Index**	**Correlation**	**pre1949**	**post1950**	**post1975**
INLAND	+AugT+pJanT+pDecT-MayP-DecP	0.53	0.59	0.51	0.58
NORTH	+AugT+pJanT+pDecT-DecP	0.49	0.53	0.51	0.60
POW	+AugT+pJanT+pDecT-MayP-AprP	0.53	0.58	0.50	0.44
PWS	+MayT+pJanT+ppAugT-MayP	0.54	0.61	0.51	0.43
CL	+pJanT+pDecT-JulP-DecP	0.45	0.39	0.50	0.67

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Chapter 3. Long term growth trends in yellow-cedar of Southeast Alaska

Abstract

Yellow-cedar is a very long-lived species found throughout Southeast Alaska and also in small populations in Prince William Sound. Tree cores were collected from over 400 trees across a large latitudinal gradient and cross-dated using standard dendrochronological techniques. Certain anomalously large and small "marker" rings were seen at all sites, suggesting a similarity in response to major climatic anomalies across the region. Long-term growth patterns going back three centuries were also similar across the sites, especially sustained below mean growth during the 1800s. Yellow-cedar at the northern limits of its distribution shows a common growth signal which may indicate the influence of larger pressure anomalies, such as El Niño-Southern Oscillation (ENSO), on the climate factors affecting the trees.

Introduction

Yellow-cedar (*Chamaecyparis nootkatensis* (D.Don) Spach) is a long-lived, slow-growing tree found along the Pacific Coast from Alaska's Prince William Sound south to the Oregon-California border (Harris 1990). In Southeast Alaska it grows from sea level to timberline, typically in mixed stands with other conifers. Yellow-cedar often grows on very wet soils on the edge of muskegs where there is less canopy competition (Hennon et al. 1990). Trees of this species found in marginal habitats can exhibit annual tree-ring growth very sensitive to changes in climate factors (Laroque 1995). Yellow-cedar trees from Vancouver Island show a common growth signal and are cross-datable (Laroque and Smith 1999). Yellow-cedar is potentially a great species for climate reconstruction since it is so long lived, with one sample over 3500 years old (Franklin and Hemstrom 1981).

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Weather station records for Southeast Alaska begin in 1828 at Sitka, and the early 1900s for several other towns. However, the reliability and regularity of weather records is variable at most stations until the post-war era starting in 1945 when data meeting the standards of First Order weather stations began. As a consequence it is difficult to compare early and modern weather records in Southeast Alaska. But even with their limitations, the pre-1945 historical data are especially useful when making long-term comparisons of environmental conditions and ecosystem responses, as in this study.

The objectives of this paper are to (1) identify consistently narrow and large pointer or "marker" ring series (Schweingruber et al. 1990) in yellow-cedar trees at the northern end of their distribution in order to see if those are consistently associated with regional climate extremes. An additional objective is to (2) determine the similarity of three to four centuries of growth patterns of cross-dated yellow-cedar trees with other tree species found along the Pacific Coast of North America. There are many possible utilizations of a study like this one, including cross-dating of other Southeast Alaska tree species or comparison to other regional chronologies to assess commonalities.

Materials and Methods

Climate Records

The Alaska Climate Research Center in Fairbanks, Alaska provided data from weather stations in Southeast Alaska beginning in 1899 at Sitka, Alaska and the early 1900s for other stations (for details see Chapter 2). Dr. Gunnar Roden (1989) supplied historic data from Sitka Magnetic Observatory going back to 1832. However, there are many gaps in the continuous collection of daily weather data at most of these stations ranging in length from one day to several decades. The data gaps obviously limit the period of cross-station comparison analyses. In addition, weather station collection locations and techniques often changed over time, especially prior to 1950 (ACRC 2006). While some of these station moves caused only a modest change in the reported variables, Cordova recordings moved in 1950 from the coastal downtown area to the airport, where its inland location near the Copper River canyon led to overall drier and much colder winter temperature recordings due to winds from the Interior (Lethcoe 2003). To avoid complication, our analyses treat these as two distinct weather stations.

Climate parameters that were compared to yellow-cedar growth include each station's daily high and low temperature (degrees Fahrenheit – original units of measure) and precipitation total (inches). We used these data to compile monthly mean temperature, monthly total precipitation, and growing season length (number of consecutive days between temperatures greater than 32 °F). We used standard techniques to fill in gaps in the dataset, as explained fully in Chapter 1. We also combined two weather stations worth of data to create longer, consistent records on the scale of Sitka Airport, Wrangell, Annette Island, and Juneau Airport (Chapter 2).

Tree Rings

We cored yellow-cedar trees at 18 sites in Southeast Alaska from 55°N to 61°N Latitude (for maps see Chapter 2). Since tree cores taken in this study were also intended to provide information on declining stands, all study sites south of 58°N Latitude centered on patches of standing yellow-cedar snags. We applied standard techniques for coring, core preparation, cross-dating, core measurement, and detrending of measurements (Chapter 2). Raw ring widths were examined for patterns of absolute growth, and detrended ring width index (normalized) values were examined for patterns of relative growth over the length of the measurable series. The detrending and normalization process of ARSTAN emphasizes "marker rings" in the ring width indices (RWI) because it transforms raw measurements to standard deviations from the mean, where the outlying values will be exaggerated to some extent.

Marker Ring Comparison

The 359 detrended and normalized tree chronologies were averaged by region into mean RWI representing Prince of Wales Island (POW), Kupreanof/ Mitkof/ Wrangell Island (INLAND), Sitka/ Poison Cove/ Goose Cove (NORTH), Cedar Bay/ Hawkins Island (PWS), and Cedar Lake (CL) (Chapter 1). Pearson correlations were calculated to compare mean RWI with monthly temperature and precipitation records from the region.

In our study, a significant marker ring was defined as any mean RWI value greater than one standard deviation from the mean. We manually compared these years to monthly mean temperature and precipitation records that had been normalized using the subtraction method (measured value times standard deviation subtracted from mean of all values). Any monthly temperature or precipitation values going back from August of the growing year of ring formation to the previous September that were greater than 1.4 standard deviations from the mean were flagged. We chose that cutoff not for any biological reason, but because it represented a natural break in the data where the majority of values fell below and only extreme outliers were included.

Only one weather record in the region is extensive enough prior to 1900 to be useful for comparison to markers rings in our chronologies. The pre-1900 data were taken at a small, exposed loghouse on Japonski Island near Sitka (Roden 1989). The daily Japonski Island mean temperatures were calculated using from 4 to 24 observations per day, and the longest period of one consistent technique was 1832 to 1845. We normalized Japonski Island temperature and precipitation data from 1832-1887 separately from later Sitka records but we used the same cutoff of 1.4 standard deviations to identify anomalous years.

Long-term Growth

All regions sampled contained trees dating back to at least 1700. We separated the population of these oldest trees, grouped them by region, and calculated average ring growth by decade 1700-2000. We also normalized this population's raw ring-width measurements (undetrended) using the subtraction method. Standard deviations were calculated from the raw ring width measurements of the trees before normalization. Regional averages of yellow-cedar growth were calculated from normalized ring-width values so that each tree was weighted equally. We graphed the growth of the defined populations from the most recent ring back to 1700, and to 1600 in the case of large cross-sections of both live and dead trees collected at Point Nemo on Wrangell Island. The raw measurements were used in this case without detrending to emphasize the actual patterns of growth in the oldest samples without introducing bias due to calibration period or the user-specified shape of detrending curve. However, even the average of trees that are several centuries old will be influenced to some degree by age-related growth trends and growth release effects, especially within decline stands and these must be kept in mind when interpreting long-term tree growth data.

Results and Discussion

Ring-width and Climate Consistency

The yellow-cedar trees from POW, INLAND, and NORTH show regional variability in the pattern of year-to-year variation in their radial growth during the last two centuries, but still have a statistically significant correlation ($r>.30$ for $p=0.01$) among the regions (Chapter 1). Narrow marker rings common to all three regions, as well as PWS and CL, include 1887, 1904, 1944, and 1987 (Figure 3.1). Large marker rings consistently seen in all five regions include 1892, 1927, 1932, 1941, 1962, and 2004. These results suggest that despite the wide geographic distribution of the samples, yellow-cedar respond similarly to some widespread climate factors. Such parallel responses are consistent with larger phenomena that drive the regional climate system such as El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Roden 1989, Wiles et al. 1996, Ware and Thomson 1999).

Figure 3.2 shows that the degree of consistency between the five reconstructed station means. Especially noteworths are positive spikes of growth in 1926, 1941, 1958, 1977, and 1998 as well as negative spikes in 1956, 1962, and 1972. There is a notable reduction in mean growing year temperature from 1971-76 at all stations, and 1965-76 at Wrangell and Juneau. Sitka is consistently cooler than Annette Island after 1942 (Figure 3.3) when the station was moved over one kilometer northeast and 13 meters uphill (ACRC 2006). Our analysis found little difference in correlation results with and without a 1.1°C adjustment to the pre-1942 values as recommended by Juday (1984).

Precipitation totals from station to station vary widely (Figure 3.3) and correlation between stations is not as strong as that seen between temperature variables. Wrangell was left out of the analysis because of gaps in precipitation records that could not be filled using other stations. Generally, individual years of especially high precipitation are consistent between stations (Figure 3.4), particularly in 1931, 1961, 1992, and 2000. Particularly low precipitation totals occurred in 1951, 1974, and 1978. Annette Island consistently receives more precipitation than Sitka and Juneau. The disjointed appearance of the Cordova annual precipitation record (Figure 3.3) is likely a function of a station move in 1942 from downtown, which is on the ocean shore, to the airport, which is inland. The dramatic difference in the precipitation totals before versus after the Cordova station move makes it difficult to assess standard deviations accurately for this station.

Markers Rings

The most common marker rings expressed in the regional ring width indices (RWI) are listed in Table 3.1. None of these shared Alaska ring-width anomalies matches the consistent narrow marker rings found in more southerly Vancouver Island yellow-cedar, even their strongest signals in 1810, 1862, 1921, and 1974. It is not surprising given the geographical separation of the two populations and the fact that radial growth of the two populations were best correlated to different climate variables.

Table 3.2 illustrates the extreme monthly temperature means that may have contributed to the most commonly expressed Alaska marker rings. August, June, April, and previous December mean monthly temperatures are often abnormally warm during large radial growth years. April and previous December temperatures that are notably cold seem to have some correlation with suppressed ring growth in yellow-cedar of Southeast Alaska. Cold temperature means in April could demonstrate a possible freezing injury to the trees as hypothesized by D'Amore and Hennon (2006).

Table 3.3 shows monthly precipitation totals that deviated from means during years with exceptional RWI values. The only consistent indicator of large rings was a wet September the year before ring formation. High December precipitation totals in the current growing year seem to have a reliable relationship with suppressed rings. It is possible that this negative effect of high December precipitation may have something to do with snowfall (e.g. branchlet or stem breakage), but it is difficult to accurately assess the amount of rain versus snowfall from precipitation records in this region (Chapter 1).

During the period that instrument records of temperature and precipitation are available (approximately since 1900), the highest (and statistically significant) Pearson correlations of detrended and normalized annual radial growth (RWI) compared to monthly climate variables are positive correlations with August, previous January, and previous December temperatures, and negative correlations with May and December precipitation (Chapter 2). These monthly variables match those mentioned previously as months most consistently exhibiting high standard deviations in marker ring years. One exception is June, which did not show a significant correlation with RWI for any region.

Notable marker rings in yellow-cedar trees often occurred in El Niño (1941, 1958, 1987, 1998) and La Niña years (1904, 1932, 1944, and 1972) (Mantua 2002). There is no consistency between either causing positive or negative growth anomalies, but the years when those phenomena are strongest in the Pacific Ocean typically triggers some response in Alaska's yellow-cedar population. La Niña typically causes large high-pressure anomalies in the subpolar latitudes and usually decreases precipitation for the Pacific Northwest (Roden 1989), whereas El Niño is associated with increased precipitation along the coast. However, in any given El Niño/ La Niña year the pressure system may be located in a slightly different area causing inconsistent weather patterns for Southeast Alaska despite being categorized under the same phenomena. Thus it is reasonable to expect both positive and negative responses in the tree-ring chronologies.

Yellow-cedar RWI has low correlation with Pacific Decadal Oscillation (PDO). In fact, periods of high growth in the late-1920s and 1960s occurred under opposite periods of PDO (Mantua 2002). The growth spike in the 1960s may be a delayed response to decreased canopy competition following a Western black-headed budworm outbreak from 1952-55 (Mask 1992). One very unique ring occurs in 1912, where the northern sample populations of yellow-cedar experienced poor growth due to the 1911 eruption of Mt. Katmai on the Alaska Peninsula. This marker ring was also seen in a small population of mountain hemlock trees cored on Mitkof Island (Viens 2001). The Juneau weather record shows extreme dry months during this time period, which may have been associated with the volcano. The suppressed 1887 ring could possibly be due to the eruption of Krakatoa (Indonesia) in 1883, as several lag times in climatic response of this length were seen following volcanoes by Viens (2001).

Comparisons of marker rings to early Sitka records are difficult to assess due to the gaps in the record and differences in average temperature calculations. The favorable growth in 1870 appears to be concomitant with several warm monthly mean temperatures. The extremely cold winter of 1875-76 and summer of 1876 likely led to the suppressed rings of 1876-78. High precipitation levels in December 1877 may have also contributed. Jacoby et al. (1999) noticed this extremely suppressed marker ring in Interior Alaska dendrochronology studies.

Long-term Growth Trends

Growth trends over the past three centuries vary from region to region in Southeast Alaska's yellow-cedar trees (Figures 3.4-3.9). All regions are in general agreement of sustained above-average growth in the 1700s and sustained below-average growth in 1800s. The average ring width in this population of trees was 0.42mm. Decadal ring-width average was the highest in the 1770s and 1940s with values above 0.5mm. The lowest decadal averages were slightly above 0.3mm and occurred 1870-1890. The Peril Strait population (Figure 3.6) showed its lowest averages 1800-1830, and its highest since 1920, with an average ring width of 0.77mm in the 1940s.

In the average of all trees (Figure 3.10), there appears an increasing and sustained high growth since the mid-1800s. This is not seen at Cedar Lake (Figure 3.8), a small population of six trees all from one small stand geographically separate from the other sites (Figure 3.9). Prince William Sound (Figure 3.9) also shows a unique pattern, likely influenced by the age-related trend of these young trees since these series were not detrended. The standard deviation of the PWS radial growth sample was generally consistent over time, but was often high in recent decades (Figures 3.4-3.8, 3.10). This may partly be explained by the fact that the population sampled was made up of live trees in cedar decline stands experiencing massive changes in stand dynamics. However, the averaging of both positive and negative growth responding trees should limit the influence on the mean value of the chronology.

The Point Nemo sample is composed of both live and dead trees, so it is important to note the possible influence of trees dropping out of the average over time (Figure 3.9). However, the standard deviation was consistent over the time scale. These trees show growth below the mean in the early-1600s, and above the mean at end of 1600s (Figure 3.9). Suppression in the 1603 ring is likely due to the eruption of Mount Huanyaputina in southern Peru in 1600 (Fagan 2000). This marker ring was also seen in a climate reconstruction based on 12 mountain hemlock from nearby Mitkof Island (Viens 2001). The hemlock reconstruction generally agrees with the yellow-cedar showing reduced growth in late-1800s to the early-1900s and increased growth in the late-1700s and mid-1900s.

One striking feature seen in the graphs is limited growth during 1840-60, which was the last glacial advance in the region (Wiles et al. 1996). The exception is at Peril Strait where there was a growth spike during the same time period, possibly due to the local warming there caused by the early stages of the retrerat of Grand Pacific Glacier in Glacier Bay. Although 1870 was also considered about the time of the end of the Little Ice Age (Fagan 2000), most Southeast Alaska trees show only a marginal increase in growth from then until the 1920s. There may be a correlation between the post-Little Ice Age warming and the onset of yellow-cedar decline, as hypothesized by Hennon et al. (2006). Yellow-cedar growth was generally low during cool periods noted for the Gulf of Alaska in 1800-15 and the late-1800s (Wiles et al. 1996). in the extreme low growth in the 1739 ring of Port Orford cedar in Oregon (Carroll and Jules 2005) is not expressed at any site in Southeast Alaska. The suppressed 1671 ring seen at Point Nemo (Figure 3.9) was not mentioned in other articles from the region.

Conclusions

Yellow-cedar cores in this study were sampled from a wide latitudinal and elevation range and yet they expressed many of the same growth patterns and marker rings. Climate records from across the region showed similarities that suggest there should have been a common growth signal if trees were responding to the weather. Monthly climate variables most consistently seen to influence ring growth include positive correlations with August, April, and previous December temperature, in addition to a negative response to May and December precipitation. Growing season did not correlate well with growth variability, however, the significant correlations with August and spring months may be a proxy for the trees actually responding to length of growing season.

The consistently nonsignificant correlation of mid-summer variables and yellow-cedar radial growth was surprising compared to other tree-ring studies of the same or related species in the region (Larocque and Smith 2005, Laroque and Smith 1999, Carroll and Jules 2005, Wiles et al. 1996, Viens 2001). This may not necessarily mean that variability at that time of year does not affect yellow-cedar diameter growth, it could simply show that the monthly climate variables used are not representative of more subtle weather patterns to which the trees respond. The correlation with winter variables is difficult to explain biologically and may be an artifact of winter temperature being the best indicator of growing year conditions because the atmospheric pressure is typically the most stable at that time of year (Roden 1989). However, the fact that prominent marker rings consistently followed winter monthly extremes suggests that there could exist a direct causative relationship.

Trees may have been responding to weather patterns set up by pressure anomalies in the Pacific Ocean, such as El Niño. Yellow-cedar diameter growth at the northern end of its distribution seemed to be markedly but inconsistently influenced by El Niño/ La Niña, especially during extreme events (Roden 1989). These are general labels for large-scale ocean-atmosphere anomalies, so it would be reasonable to infer that they do not always affect diameter growth in the same direction. Yellow-cedar trees do not appear to respond to Pacific Decadal Oscillation (Mantua 2002).

The correlation between ring width and nineteenth century weather records from Sitka, Alaska is not consistent. This likely resulted from the various measurement techniques used to calculate daily average temperature from 1828 to 1887 (Roden 1989).

Long-term growth of yellow-cedar in Southeast Alaska generally matches other species from the Pacific Northwest Coast (Viens 2001, Wiles et al. 1996). A distinctive low period of growth lasting from the mid-1800s to the early-1900s is consistent across most of our samples. It was also noted in mountain hemlock from Mitkof Island (Viens 2001) and other studies (Wiles et al. 1996, Larocque and Smith 2005).

It is my hope that other dendrochronology studies will be conducted in Southeast Alaska and that the information provided here may aid in the cross-dating of yellow-cedar and other tree species. Future articles using these data will assess their implications for the cedar decline phenomenon.

Figures

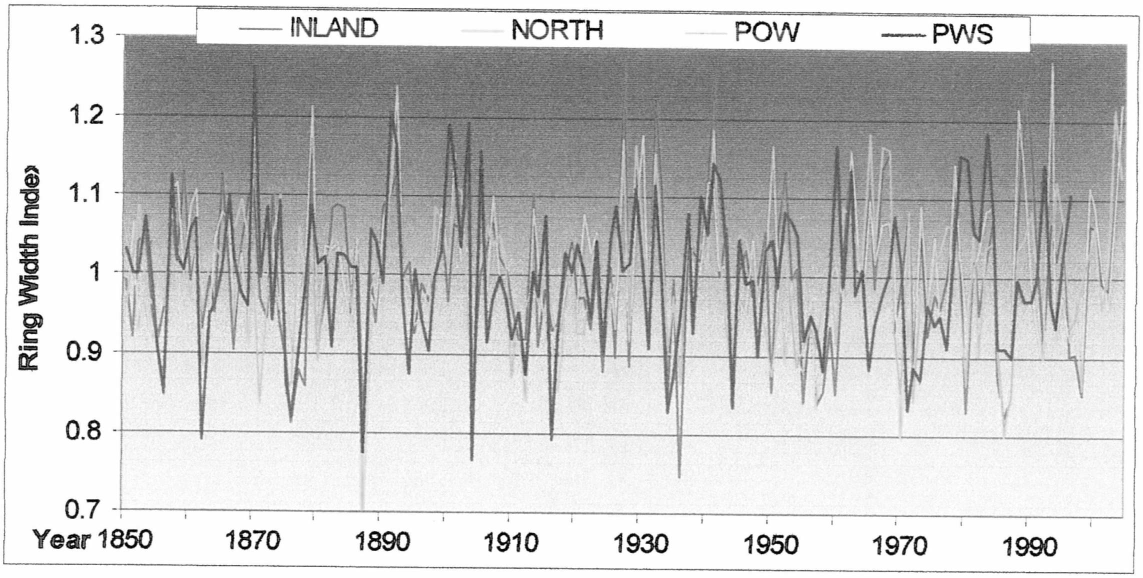

Figure 3.1. Ring width index (RWI) for yellow-cedar tree-ring series of Alaska.

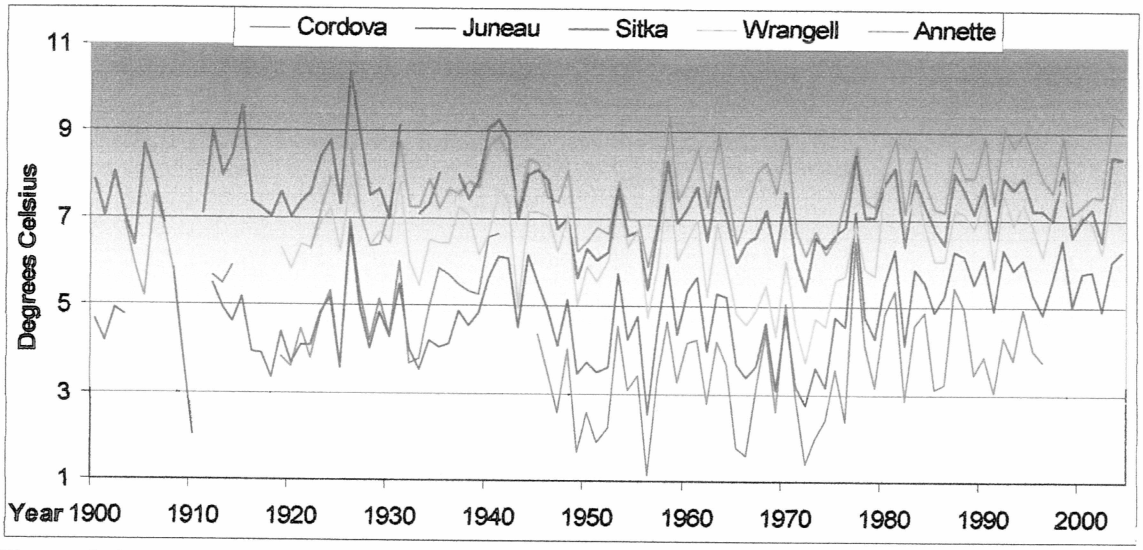

Figure 3.2. Mean annual temperature. Recorded growing year mean temperature reconstructed for five weather stations in Southeast Alaska. Growing year calculated September-August.

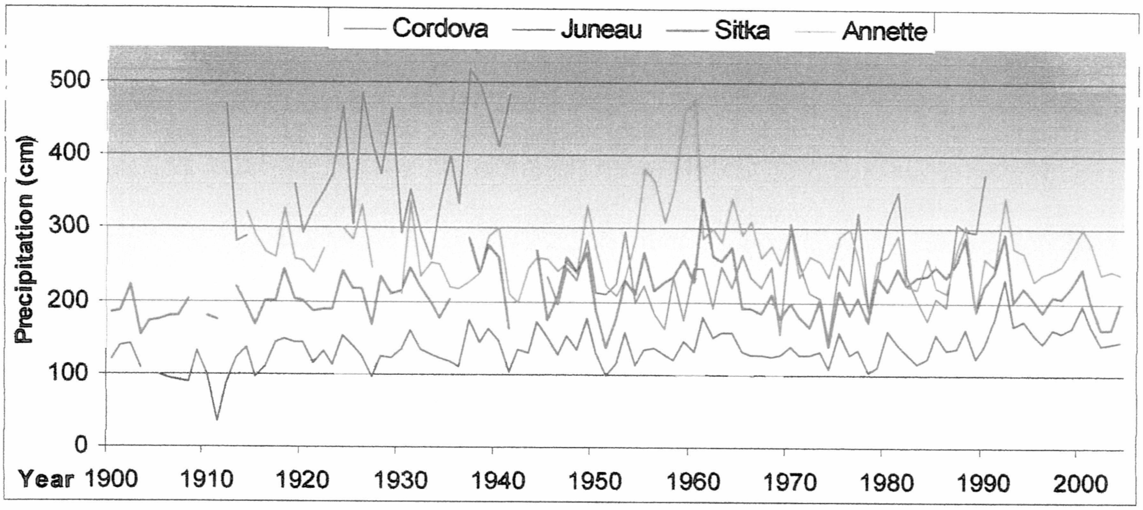

Figure 3.3. Annual total precipitation. Recorded growing year total precipitation reconstructed for four weather stations in Southeast Alaska. Growing year calculated September-August.

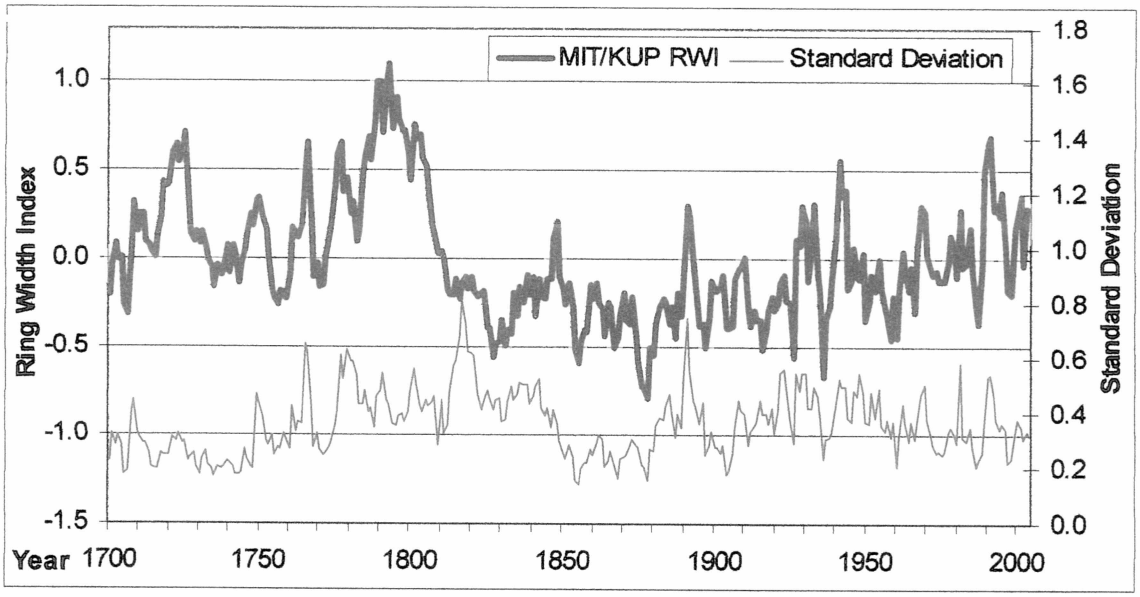

Figure 3.4. Average growth since 1700—INLAND. Long-term growth of 18 yellow-cedar trees from Mitkof and Kupreanof Islands.

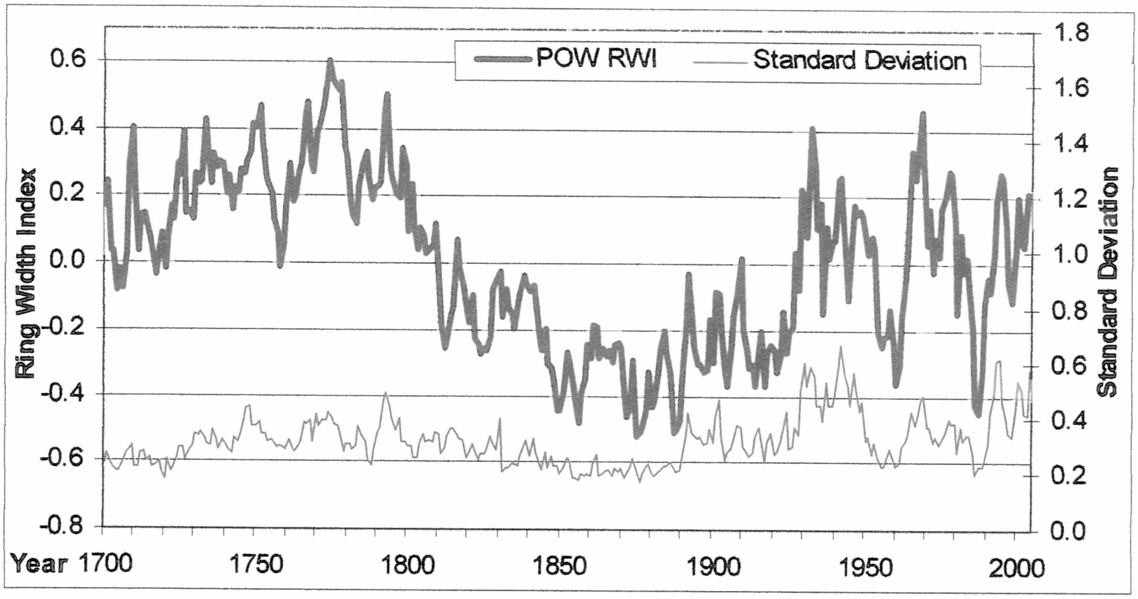

Figure 3.5. Average growth since 1700—POW. Long-term growth of 45 yellow-cedar trees from Prince of Wales Island.

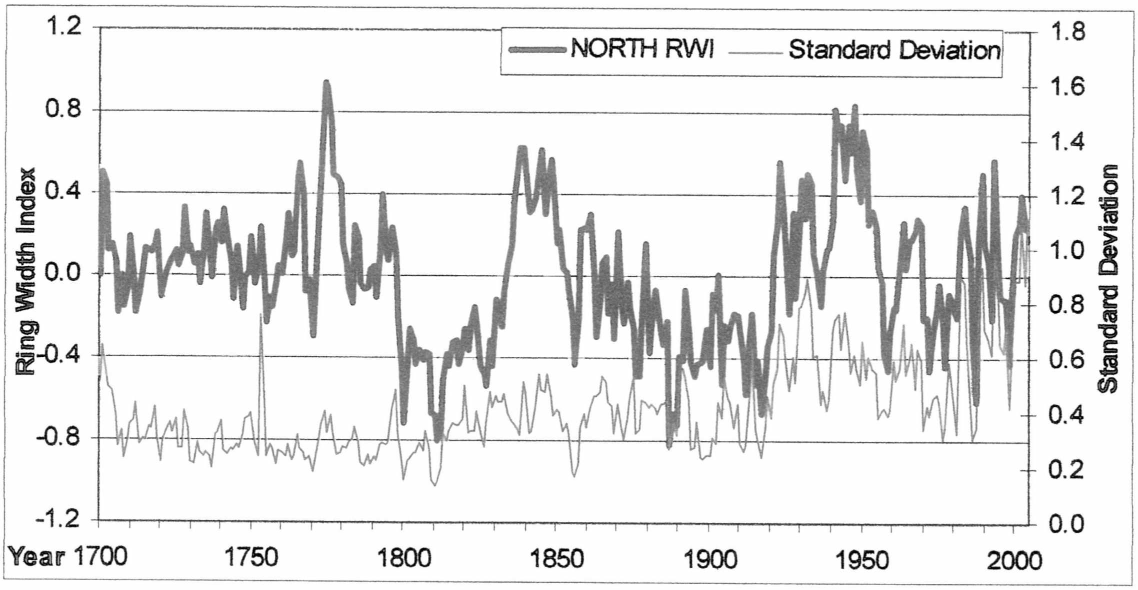

Figure 3.6. Average growth since 1700—NORTH. Long-term growth of 16 yellow-cedar trees from Peril Strait.

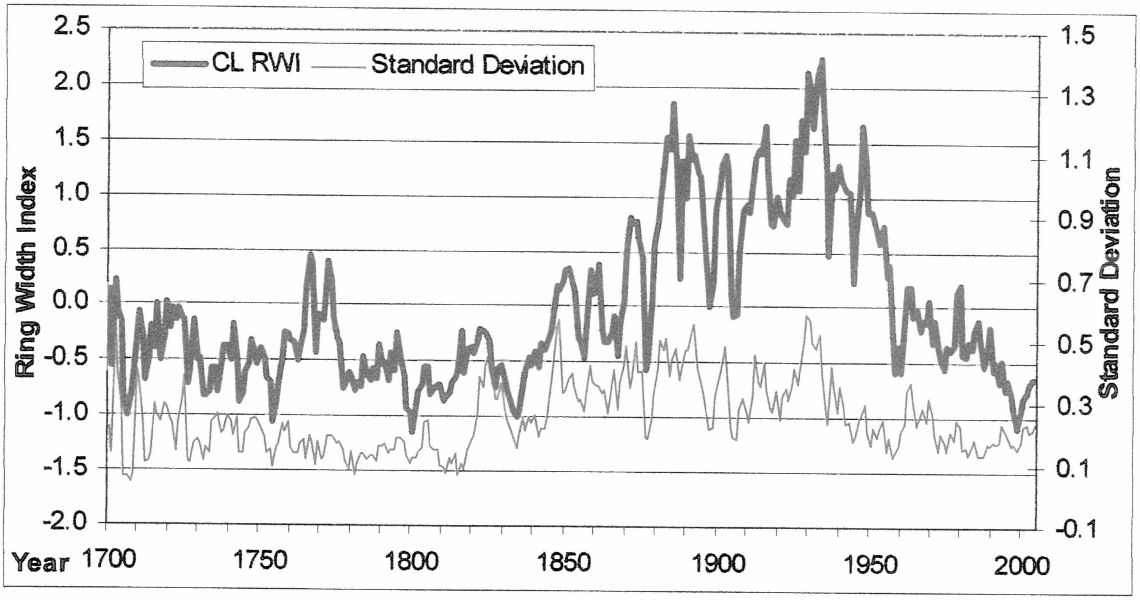

Figure 3.7. Average growth since 1700—CL. Long-term growth of 6 yellow-cedar trees from Cedar Lake.

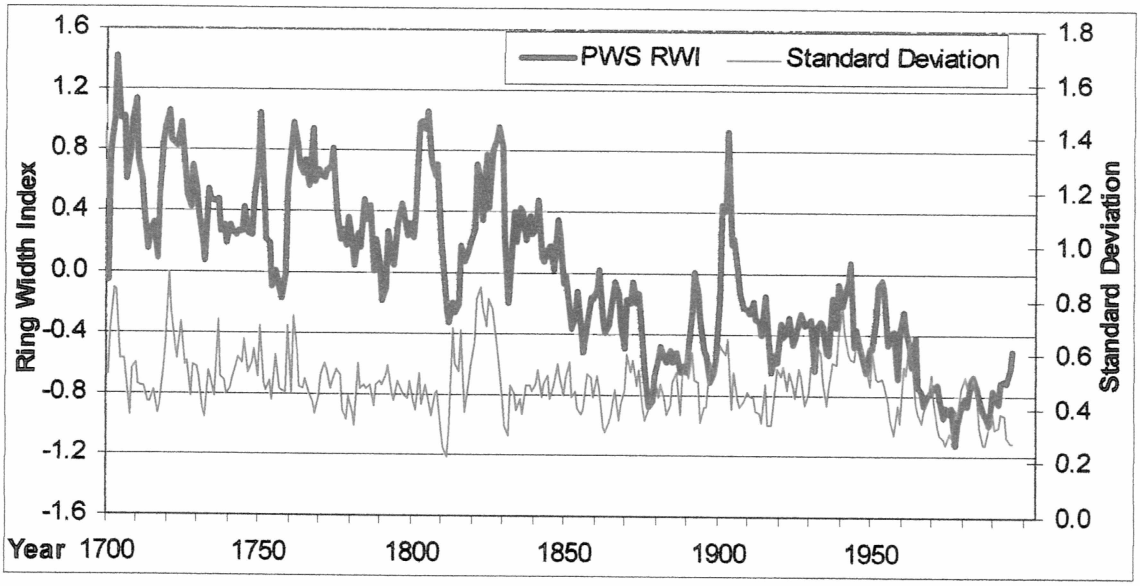

Figure 3.8. Average growth since 1700—PWS. Long-term growth of 14 yellow-cedar trees from Prince William Sound.

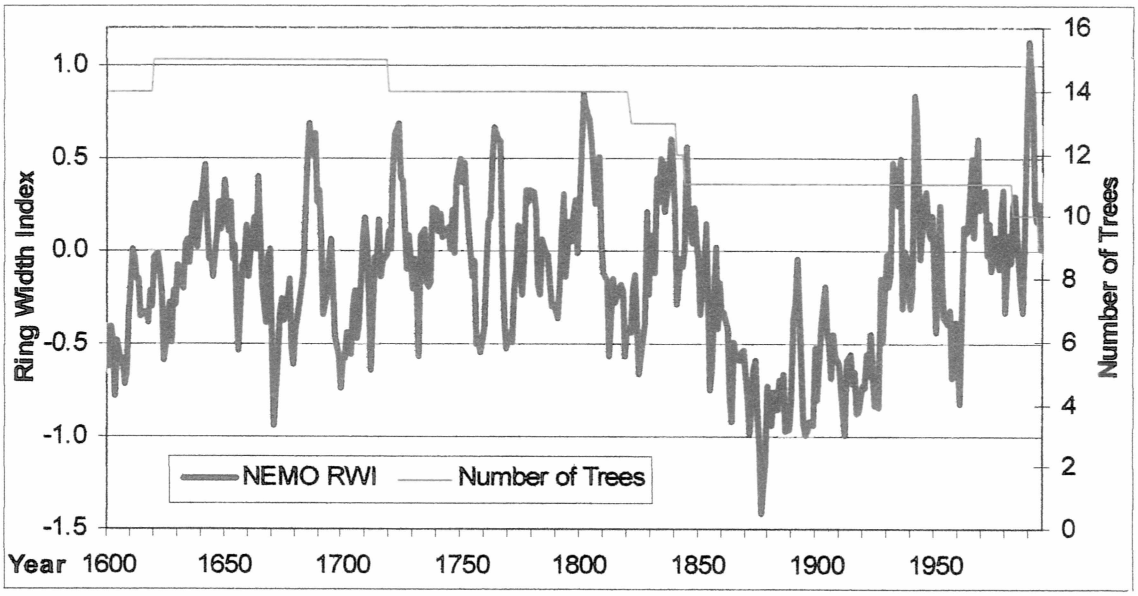

Figure 3.9. Average growth since 1600—NEMO. Long-term growth of yellow-cedar trees and snags from Point Nemo, Wrangell Island.

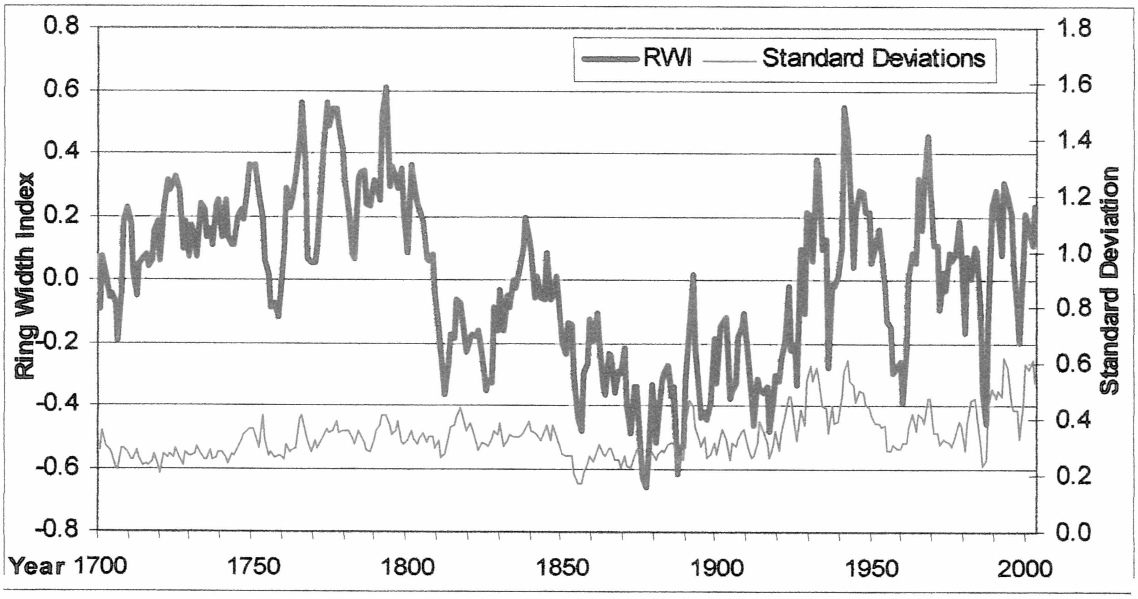

Figure 3.10. Average growth since 1700—All sites. Long-term growth of 92 yellow-cedar trees from throughout Southeast Alaska.

Tables

Table 3.1. Common marker rings expressed in individual trees and regional series. Tables divided into large (a) and small (b) marker rings where "X" represents the ring was present at all sites comprising a region and "s" means not all sites showed that marker. A significant marker ring was defined as any mean RWI value greater than one standard deviation from the mean.

a) Large Marker Rings

Ring Year	INLAND	NORTH	POW	PWS	CL
2004	X	X	X		X
1978		X	s		X
1968	X		X		
1967	X		X		
1962	X	X	s	X	
1941	X	X	X	X	
1932	X	X	X	X	X
1929	X		X	X	X
1927	X	X	X		X
1901		X	s	X	
1892	X	X	X	X	
1891	s	X	X	X	X
1870	s	X		X	

b) Small marker rings

Ring Year	INLAND	NORTH	POW	PWS	CL
1998	X	X			X
1987	X	X	X	X	X
1986	X	X	X		
1972		X	X		
1958	X			X	X
1957	X	X			X
1955	X	X	s		X
1954		X	X		
1944	X	X	s	X	X
1936	X		X		X
1916	s	s		X	
1912	s	X		X	
1904	X	X	X	X	X
1887	X	X	X	X	X
1878	s	s			
1877	s	s			
1876	s	s	X	X	X
1862	s	X		X	X
1856		X		X	X

Table 3.2. Extreme monthly temperature variables occurring temporally near marker ring years. Capitalized months represent above normal monthly mean temperatures and lower case months represent below normal (at least 1.4 standard deviations). Months with “1” and “2” mean they occurred in the year prior or two years prior to ring formation.

a) Large Marker Rings

Ring Year	Sitka	Annette	Wrangell	Juneau	Cordova
2004	AUG JUN NOV2	AUG JUL JUN MAY APR JAN1 DEC2 NOV2	AUG JUN MAY	AUG JUL JUN MAY FEB	X
1978	dec1 nov1 FEB1	AUG1 FEB1	dec1 AUG1 jun1 FEB1	dec1 AUG1 FEB1 JAN1 NOV2	nov1 AUG1 JUL1 FEB1 JAN1 DEC2 NOV2
1968	apr mar1 nov2 oct2	MAY AUG1 JUN1	sep apr sep1 jul1 mar1 oct2	mar1 nov2 oct2	oct2
1967	mar nov1 oct1 may1 jan1	AUG JUN	sep jul mar oct1 aug1 may1 apr1 jan1	mar nov1 oct1 may1 jan1	oct1 may1 mar1feb1
1962		JUL1		jun	mar dec1
1941	AUG JUN APR MAR SEP1 JUL1 APR1 JAN1 DEC2	APR MAR OCT1 SEP1 APR1 DEC2	AUG JUN MAY APR DEC2	AUG APR MAR APR1 DEC2	SEP AUG JUN MAR DEC1 JUL1 JUN1 MAY1 APR1
1932	jun APR1 JAN1 DEC2	JAN1 DEC2	APR JAN1 DEC2	jul jun JAN1 DEC2 oct2	feb APR1 JAN1 DEC2
1929	SEP	jul apr		aug1	SEP
1927	SEP AUG JUL JUN OCT1 SPET1 AUG1 JUL1 JUN1 MAY1 APR1 MAR1 JAN1 DEC2	apr	AUG JUL apr jun1 MAR1 JAN1 DEC2	apr MAR1 JAN1	apr OCT1 SEP1 AUG1 JUN1 MAY1 APR1 MAR1 JAN1 OCT2
1901		X	X	oct2	X
1892	X	X	X	X	X

Table 3.2 continued

Ring Year	Sitka	Annette	Wrangell	Juneau	Cordova
1891	X	X	X	X	X
1870	SEP AUG JUL APR1 MAR1 JAN1	X	X	X	X

b) Small Marker Rings

Ring Year	Sitka	Annette	Wrangell	Juneau	Cordova
1998	FEB			FEB DEC1 SEP1 AUG1 JUN1 MAY1	MAY1 oct2
1987	OCT1 apr1 nov2 oct2	FEB DEC1	MAR FEB SEP1	AUG DEC1 OCT1 JAN1	DEC1 apr1 nov2 oct2
1986	apr nov1 oct1 jun1 JAN1	OCT1 MAR1 nov2 oct2	OCT1 MAR1 nov2	JAN JAN1 nov1	apr nov1 oct1 aug1 jun1 may1 apr1 JAN1
1972	sep apr feb jan dec1 oct1 may1 jan1	MAR nov1 oct1 JAN1	MAR nov1 JAN1	apr mar feb oct1 may1 jan1	sep mayaprmarfebjan mar1 jan1
1958	SEP1 AUG1 oct2	apr feb jan JUL1	sep jun apr mar feb jan dec1 oct1	JUN SEP1 AUG1	oct2
1957	SEP AUG oct1 mar1 feb1 dec2 oct2 sep2	JUL JUN APR SEP1 oct2	JUN APR SEP1 AUG1	SEP AUG oct1 jun1 dec2 nov2 oct2	oct1sep1 jun1 may1 mar1 feb1 nov2
1955	sep aug jun may mar jul1 apr1	SEP oct1 dec2 nov2	SEP AUG oct1 sep1 feb1 dec2 nov2	may apr1	aug jun may apr1
1954	jul apr JUL1	aug may mar NOV1 jul1	mar nov1 apr1	apr	apr
1944	SEP2	NOV jul1 OCT2	apr OCT2	JAN DEC1 NOV1 OCT2	dec2
1936	AUG JUL JUN feb DEC1 FEB1	DEC2	jul1 mar1	JUN oct1 mar1	AUG JUL JUN

Table 3.2 continued

Ring Year	Sitka	Annette	Wrangell	Juneau	Cordova
1916	jan JUL1 JUN1 MAY1 APR1 MAR1	AUG JUN feb DEC1 mar1	JUN feb DEC1 mar1	jan sep1 aug1 JUL1 MAY1 MAR1	X
1912	MAY FEB OCT1 apr1	jan JUL1 MAR1 DEC2	X	aug MAY AUG1 JUL1 jan1	SEP1 aug may1 apr1
1904	aug jul jun mar feb DEC1 dec2	aug MAY may1 apr1	X	jul jun	X
1887	jul feb OCT2	X	X	X	X
1878	MAY1 APR1 nov2	X	X	X	X
1877	MAY APR nov1 aug1 jul1 jun1 mar1 feb1 jan1 dec2 nov2	X	X	X	X
1876	aug jul jun mar feb jan dec1 nov1 OCT1 mar1 nov2	X	X	X	X
1862	sep may apr jan dec1 SEP1	X	X	X	X
1856	MAR FEB	X	X	X	X

Table 3.3. Extreme monthly precipitation variables occurring temporally near marker ring years. Capitalized months represent above normal monthly precipitation totals and lower case months represent below normal (at least 1.4 standard deviations). Months with "1" and "2" mean they occurred in the year prior or two years prior to ring formation.

a) Large Marker Rings

Ring Year	Sitka	Annette	Juneau	Cordova
2004	jun MAR apr1	oct2	may SEP1 apr1	X
1978	aug1 may1 APR1	jun jan FEB1	sep	NOV2
1968	SEP1	SEP may APR SEP1 JUL1 apr1 mar1 FEB1	apr1	FEB
1967	SEP MAY1 nov2	SEP JUL apr mar FEB MAY1 apr1 MAR1 OCT2	apr MAY1 MAR1 nov2	JAN1
1962	JUN JAN AUG1 JUL1 JUN1 APR1 DEC2 OCT2	FEB JUL1 APR1 MAR1 JAN1 DEC2 NOV2 OCT2	AUG1	
1941	OCT2 aug	AUG1	aug feb	JUL APR MAR SEP1 DEC2
1932	JUL JUN OCT1 MAY1 mar	DEC2	aug JUN MAY1	AUG JAN1
1929	JAN1 sep	sep AUG jun1 MAR1	jun1 JAN1	MAY FEB DEC1 NOV1 SEP1 FEB1
1927	jul MAR DEC1 sep1 JAN1	sep1 JAN1 DEC2	jul sep1 aug1	AUG FEB OCT1 APR1 MAR1 JAN1 NOV2 OCT2
1901	jul APR1	X	AUG jul APR1	X
1892	X	X	X	X

Table 3.3 continued

Ring Year	Sitka	Annette	Juneau	Cordova
1891	X	X	X	X
1870	FEB1	X	X	X

b) Small Marker Rings

Ring Year	Sitka	Annette	Juneau	Cordova
1998	DEC1 JUL1 FEB1	AUG DEC1	DEC1 JUL1 FEB1	X
1987	SEP JUN OCT1 sep1 MAR1	SEP jul OCT1 nov2	JUN OCT1 sep1 MAR1 DEC2 nov2	JUN JAN DEC1 oct2
1986	sep MAR JUN1 FEB1 JAN1	nov1	sep MAR DEC1 nov1 FEB1 JAN1	oct1
1972		jul1 nov2	AUG jul	MAY1
1958	JUL MAY NOV1 APR1 DEC2 NOV2	SEP AUG jun MAY JAN NOV1 jan1 NOV2	mar aug1 jan1 DEC2 NOV2	JUL jun1
1957	DEC1 NOV1 AUG1 MAY1	jan NOV1 AUG1 JUN1 MAY1 APR1 dec2 OCT2	aug jan DEC1 NOV1 AUG1	jun
1955	MAY MAR FEB DEC1 FEB1 DEC2	AUG JUN MAY JAN DEC1 FEB aug1	aug1 OCT2	
1954	FEB DEC1	aug FEB MAY1	aug OCT1 FEB1 OCT2	
1944	sep DEC1 NOV1 SEP1	JUL1 mar1	MAR DEC1 SEP1	
1936	jun APR JUL1	feb sep1	aug jun oct1	MAY JAN FEB1 DEC2

Table 3.3 continued

Ring Year	Sitka	Annette	Juneau	Cordova
1916	JUN jan jul1 may1 APR1 oct2	jan MAR1	jan jul1 oct2	X
1912		may1	jan sep1 aug1 jul1 may1 apr1 mar1 nov2 oct2	
1904		X	JUN oct2	X
1887	JUL NOV1 OCT1 SEP1 FEB1	X	X	X
1878	DEC2	X	X	X
1877	DEC1	X	X	X
1876	APR1	X	X	X
1862	jun1	X	X	X
1856	JUL	X	X	X

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Conclusion

The yellow-cedar trees of Southeast Alaska are an important species both ecologically and commercially, although little is known about the factors affecting its annual growth. This study has shown that the tree-rings from the species are cross-datable in this region. In addition, there is a statistically significant correlation between diameter growth and climate variables in our dataset. However, most individual tree-ring series exhibit extreme short-term variation in growth patterns most likely due to growth release and suppression based on microsite factors. To account for these deviations we found it necessary to apply a cubic-smoothing spline to the raw ring width measurements. Pearson correlation values were increased by normalizing, detrending, and averaging individual ring width indices into larger groups based on geographical proximity.

Climate records in Southeast Alaska lack continuity and have uneven reliability prior to the 1940s. We used proxy stations to attempt to fill in gaps in monthly temperature and precipitation measurements at several stations in the area. Long-term climate graphs suggest a distinctive warming trend in Southeast Alaska during the period 1977-2004. These data should be treated with caution, but are very useful when compared with continuous data such as tree-rings. The monthly climate variables we used suggest that winter conditions in the year prior to ring formation may have the strongest influence on annual diameter growth. It may be that yellow-cedar simply responded to weather patterns set up by pressure anomalies in the Pacific Ocean, as many large and small growth rings occurred in years of pronounced El Niño/ La Niña events. The oldest trees in the records exhibited a distinctive period of low growth lasting from the mid-1800s to the early-1900s.

Future dendrochronology studies in Southeast Alaska using yellow-cedar and other species are warranted based on this study. The information provided here should be helpful in determining a possible climate-based cause for the cedar decline phenomenon.

Appendix

Table A.1. Monthly mean temperature at Sitka, Alaska with reconstructed values for missing recordings. Values reconstructed from Little Port Walter marked *, from Port Alexander marked ^, and from an average of Annette Island and Juneau Downtown marked +. Measurements taken at Sitka Magnetic Observatory and the old loghouse on Japonski Island were modified to match the scale of Sitka Airport measurements and are here listed in italics.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	34.0	40.6	38.5	44.2	49.4	56.0	58.4	61.6	53.0	–	–	–
2003	40.9	39.7	36.5	43.4	48.3	53.0	58.0	57.5	54.1	49.9	39.8	39.0
2002	37.5	34.6	32.6	39.0	46.3	52.5	54.3	56.4	52.8	49.1	47.4	39.6
2001	40.6	35.4	36.8	41.2	44.6	52.8	55.0	58.1	52.7	44.7	38.1	36.1
2000	33.5	36.2	39.1	41.0	46.6	51.5	55.2	56.0	51.1	45.3	42.1	38.0
1999	*34.7	*34.2	37.2	40.9	43.7	51.4	54.3	55.6	51.4	45.9	40.5	39.1
1998	*34.4	*42.2	*40.2	*43.4	47.8	*53.6	*56.1	*55.6	*51.9	*47.7	^40.0	^35.2
1997	*33.5	*38.9	*36.6	*43.5	*48.3	*53.0	*55.6	*59.4	*55.5	^47.9	*42.7	*39.9
1996	28.7	36.3	38.7	44.1	48.3	52.8	55.9	56.5	51.7	44.1	37.6	33.2
1995	36.5	36.1	37.5	45.7	49.6	53.6	55.9	55.6	57.3	46.8	38.5	36.0
1994	38.6	29.9	40.5	44.4	47.7	53.4	56.2	58.8	52.6	45.9	35.9	34.6
1993	33.9	38.3	39.9	46.0	51.0	54.6	58.7	58.9	54.3	50.1	41.0	41.6
1992	40.9	38.8	39.8	43.4	47.6	53.0	55.7	56.2	48.7	44.2	42.0	34.3
1991	33.5	39.1	35.9	43.0	47.5	51.1	54.7	55.8	53.2	44.8	43.6	39.5
1990	34.1	32.6	39.9	44.9	49.2	54.6	57.8	59.1	54.2	43.7	34.7	32.7
1989	32.4	32.8	36.2	44.8	46.7	52.5	57.6	58.2	54.5	45.6	39.2	42.3
1988	35.1	37.9	39.5	41.7	48.6	53.9	55.7	57.2	50.8	47.3	41.6	37.1
1987	39.0	39.5	37.8	43.8	47.8	50.9	55.9	57.6	53.3	46.4	42.8	37.6
1986	39.4	33.7	39.3	38.3	46.2	51.3	55.0	55.9	55.1	50.6	39.4	41.4
1985	42.9	34.4	37.7	39.9	45.8	50.1	55.5	55.3	53.1	43.0	28.8	39.0
1984	38.2	38.5	42.4	44.0	48.4	52.2	55.1	57.0	53.0	44.4	37.9	34.4
1983	38.5	40.3	40.2	43.9	48.1	55.4	57.8	57.3	50.3	45.2	38.7	32.2
1982	29.0	31.8	37.1	39.3	44.8	51.9	55.3	55.6	53.4	45.4	37.0	38.1
1981	44.0	38.6	42.2	41.1	51.4	53.4	56.9	58.5	53.0	46.7	42.5	34.9
1980	31.4	40.9	38.8	44.1	48.5	53.1	56.2	56.3	52.1	48.8	42.2	31.6
1979	33.5	27.1	40.8	43.2	47.4	52.4	58.0	59.5	56.4	49.7	44.1	33.9
1978	35.1	39.7	38.4	44.0	47.7	52.9	55.7	58.5	54.0	47.6	37.7	35.8
1977	41.0	43.0	38.1	42.9	47.9	54.4	57.4	59.7	53.9	47.0	34.4	29.1
1976	36.5	33.1	36.6	43.9	45.2	50.8	57.9	56.4	53.3	46.2	43.8	39.7
1975	30.9	30.9	36.1	40.7	47.3	49.1	55.6	55.9	53.1	45.9	36.8	35.5
1974	28.4	35.9	35.8	42.6	47.0	50.9	55.6	57.7	54.5	47.1	40.7	39.2
1973	31.7	35.0	38.1	42.9	46.5	51.4	54.9	54.5	52.9	44.1	32.2	37.8
1972	25.6	29.5	34.9	36.8	46.8	50.7	56.5	56.5	51.0	43.8	41.4	34.7
1971	27.8	35.2	35.6	40.2	43.1	51.1	56.4	58.3	51.2	42.6	39.3	30.0
1970	33.0	41.6	41.4	41.1	46.2	51.3	53.4	53.8	51.2	45.5	38.9	31.2
1969	22.2	34.8	38.0	42.5	49.2	53.9	54.1	54.3	53.7	49.3	41.5	42.4
1968	30.2	37.6	40.0	39.2	49.0	52.3	57.1	58.5	51.5	44.0	41.0	31.5

Table A.1. continued

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	32.6	37.1	32.5	42.3	48.4	52.7	55.5	58.7	53.3	46.8	39.4	36.4
1966	29.4	35.9	37.9	40.9	44.4	52.8	56.0	55.1	53.2	42.7	35.7	35.7
1965	31.9	34.1	38.6	42.2	43.9	49.6	55.6	55.9	53.1	46.4	38.6	33.3
1964	36.4	38.3	35.3	39.6	45.2	53.6	54.7	55.4	52.7	46.3	36.8	26.1
1963	36.5	41.7	37.7	41.2	49.5	50.6	56.4	58.5	56.3	48.1	34.8	39.5
1962	35.4	35.7	35.6	41.9	45.9	50.3	55.7	57.3	52.8	48.0	43.1	38.2
1961	39.2	37.9	39.1	41.7	49.3	52.0	56.1	56.7	52.3	44.3	36.7	33.5
1960	36.1	38.4	37.7	43.3	49.3	51.0	55.5	55.2	51.7	47.1	40.1	39.9
1959	33.0	36.0	36.8	41.9	48.0	54.5	55.0	55.6	51.4	45.2	39.8	38.1
1958	39.5	38.7	38.2	45.2	48.6	55.4	58.2	57.0	51.2	45.1	38.5	37.8
1957	31.4	33.8	38.7	41.0	48.3	52.8	55.8	59.7	56.6	47.8	44.1	35.0
1956	31.2	29.2	34.4	41.2	46.8	50.5	55.5	56.0	51.3	41.4	42.3	33.8
1955	38.3	35.2	34.1	39.6	43.3	49.5	55.3	53.5	50.9	43.0	32.7	28.7
1954	30.3	31.1	36.5	37.2	47.6	52.4	54.0	57.7	54.6	46.9	43.9	34.6
1953	28.6	38.0	36.5	44.4	48.4	53.8	58.5	58.2	53.0	47.2	40.7	39.2
1952	27.5	35.6	36.0	40.0	45.9	51.4	55.5	57.9	53.1	48.9	42.8	39.7
1951	30.4	32.4	31.2	40.6	46.9	51.5	58.0	56.9	54.5	43.4	39.1	32.1
1950	24.2	34.1	37.8	39.7	44.6	54.8	53.9	57.8	52.6	44.6	32.2	38.0
1949	33.2	28.5	39.0	41.2	45.7	48.6	53.5	55.3	54.0	45.9	43.9	29.7
1948	36.5	28.1	35.7	38.9	48.9	53.8	56.0	55.5	51.3	43.9	37.8	28.4
1947	30.2	35.0	40.3	42.0	47.7	53.3	57.4	56.4	54.4	47.7	42.2	38.4
1946	39.4	37.8	36.8	40.9	49.6	55.1	56.5	55.5	53.0	45.6	36.7	32.6
1945	39.6	39.2	38.7	39.8	45.1	53.8	54.0	54.9	55.0	49.6	40.7	37.5
1944	40.4	38.1	37.3	41.5	46.8	52.4	56.0	56.2	53.9	53.0	46.4	40.4
1943	31.3	36.9	36.6	43.4	47.2	52.8	55.1	56.3	53.0	47.3	45.3	42.4
1942	45.1	42.1	39.6	45.0	*49.7	54.1	57.9	57.6	56.2	48.4	37.0	34.2
1941	39.1	39.1	45.8	47.5	49.5	56.3	58.1	61.0	54.7	48.6	41.9	38.4
1940	42.2	39.2	41.2	47.5	50.2	54.7	59.7	58.4	55.9	50.1	41.1	41.2
1939	39.4	34.2	37.7	40.6	47.0	52.7	57.3	55.6	52.7	46.2	43.6	43.7
1938	38.6	32.3	38.9	43.7	47.0	50.6	54.2	56.7	57.1	50.5	43.2	38.8
1937	34.5	33.1	41.7	42.9	47.4	54.9	55.8	55.8	54.9	50.8	42.6	34.6
1936	37.2	+25.1	36.0	43.2	47.9	58.0	59.0	60.7	53.9	51.8	47.7	37.4
1935	34.4	42.3	35.6	44.8	48.0	55.0	56.1	56.5	54.8	44.4	41.3	42.8
1934	37.0	41.6	40.0	44.3	50.0	52.1	57.4	58.2	53.9	48.9	43.6	38.4
1933	33.6	35.8	37.7	40.3	48.7	51.8	55.8	57.1	52.4	44.2	43.3	21.9
1932	35.6	33.9	40.9	45.4	49.9	+50.1	54.9	58.2	52.3	48.9	39.6	35.6
1931	43.5	41.0	40.2	46.8	49.5	55.5	58.2	59.7	55.6	47.5	39.7	37.7
1930	29.2	35.0	35.7	41.8	46.3	51.9	55.9	59.4	52.3	45.9	44.1	44.8
1929	38.3	37.5	38.4	39.8	46.7	53.4	55.3	58.0	55.8	48.9	42.2	32.9
1928	38.9	38.8	38.3	42.8	48.3	54.6	56.2	55.0	53.4	46.1	43.8	39.0
1927	37.9	40.0	39.3	39.8	48.6	56.3	59.4	61.7	56.0	46.8	36.7	33.6
1926	46.4	41.4	45.8	47.1	51.4	57.7	59.8	61.5	56.8	51.3	45.0	40.2
1925	32.4	34.3	38.7	41.7	48.5	53.7	56.6	57.8	55.6	50.7	44.7	45.6
1924	39.7	39.4	41.3	41.8	49.8	56.4	56.6	57.9	53.1	46.4	42.8	36.2
1923	34.8	37.8	39.8	45.3	49.9	55.3	59.5	62.7	55.6	52.1	45.4	38.2

Table A.1. continued

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1922	37.6	32.6	37.3	41.7	48.0	54.1	56.2	58.5	52.8	49.0	44.4	34.8
1921	34.1	37.3	35.8	42.3	46.6	55.2	55.7	57.7	54.7	48.3	39.7	39.1
1920	32.6	40.4	37.2	39.1	44.5	51.8	56.7	56.6	52.1	45.1	42.4	39.3
1919	38.5	36.7	35.7	43.8	47.0	51.8	55.9	57.8	55.2	46.5	38.0	37.1
1918	38.6	35.2	35.4	40.4	47.3	53.5	57.8	54.8	53.4	47.5	42.6	37.0
1917	32.4	35.0	37.9	43.8	47.8	51.6	54.9	57.1	53.7	45.8	43.1	30.5
1916	26.6	37.4	35.8	45.1	47.7	52.8	55.8	57.4	52.1	48.8	42.0	36.1
1915	41.7	39.7	46.6	45.8	54.6	55.9	61.4	59.6	55.3	47.4	41.4	40.6
1914	36.3	41.7	41.6	46.4	49.3	54.1	55.1	56.2	52.6	52.7	42.9	37.4
1913	32.6	39.9	39.7	41.8	48.1	55.0	56.5	57.8	53.1	46.9	43.3	42.7
1912	39.7	43.0	41.5	43.9	52.9	52.7	56.8	54.9	54.2	48.5	42.5	39.9
1911	29.0	37.4	37.0	38.8	45.6	51.0	56.9	59.7	55.3	51.0	38.9	
1910	36.1	32.8	–	–	–	–	–	57.0	56.2	46.3	40.4	39.4
1909	–	–	–	–	47.9	53.7	56.0	55.4	52.6	46.0	34.8	36.1
1908	38.7	37.6	38.5	40.9	46.5	52.4	–	–	–	–	–	–
1907	30.5	32.5	34.4	42.2	50.9	51.6	56.0	56.2	54.3	48.0	43.6	39.9
1906	29.3	39.4	41.1	43.6	49.4	54.1	56.7	56.4	52.5	48.4	42.5	34.8
1905	39.6	39.4	44.7	43.8	48.7	54.5	57.9	58.0	52.4	47.7	44.4	40.8
1904	33.7	27.6	34.3	42.6	46.0	48.7	52.2	54.5	52.5	48.3	42.7	41.7
1903	37.0	36.0	34.4	41.7	46.3	54.7	56.7	59.1	53.0	47.0	38.8	42.6
1902	39.3	41.8	35.9	42.4	47.3	55.6	57.1	55.8	52.1	49.1	39.8	30.2
1901	37.2	32.4	38.8	41.2	46.1	52.0	56.4	55.4	53.5	48.5	40.4	40.0
1900	38.8	35.2	39.9	42.7	47.0	53.4	56.9	56.8	53.0	44.3	38.9	40.1
1899	–	–	–	–	44.5	50.2	58.1	56.1	53.0	44.4	45.8	39.6
	–	–	–	–	–	–	–	–	–	–	–	–
1877	35.4	36.1	38.7	44.2	52.5	–	–	–	–	–	–	–
1876	25.3	23.9	28.9	38.8	46.0	51.4	53.6	53.8	51.8	47.1	34.9	39.4
1875	26.2	37.8	30.9	39.2	45.5	52.0	55.8	55.8	54.0	51.1	26.8	27.3
1874	23.5	30.9	32.2	45.1	51.6	54.7	56.3	60.4	52.7	44.4	30.6	36.0
1873	28.8	33.3	35.4	41.0	46.4	51.4	54.1	54.5	51.4	46.4	38.5	33.8
1872	36.7	31.5	40.1	39.4	46.8	48.9	56.5	56.5	50.7	45.0	36.5	36.1
1871	27.9	34.2	35.8	39.2	45.9	48.2	52.9	53.4	50.4	46.2	32.5	31.6
1870	30.9	35.2	33.3	41.9	46.6	52.5	57.2	59.7	54.7	47.3	38.8	36.0
1869	39.2	37.9	41.9	43.3	47.8	52.0	56.5	55.2	52.7	47.7	42.3	39.4
1868	28.9	36.0	37.2	44.2	44.8	54.1	55.2	55.6	51.6	49.1	41.4	37.8
1867	27.9	25.5	34.9	40.6	47.1	50.7	54.0	50.9	49.5	43.3	39.7	29.1
1866	28.9	32.0	35.2	41.0	46.4	50.9	53.6	54.5	48.6	41.9	40.1	34.5
1865	34.2	33.1	31.3	38.8	44.4	50.7	53.4	53.1	50.0	43.5	38.5	32.0
1864	32.5	35.2	36.0	40.3	47.5	53.1	53.4	53.6	50.7	46.9	38.8	31.5
1863	31.8	27.0	35.2	38.7	43.5	51.8	55.4	56.1	54.9	45.1	37.0	31.1
1862	25.2	27.9	34.9	36.5	42.8	50.5	55.8	54.9	48.2	41.4	41.0	36.9
1861	31.5	36.7	36.7	40.5	46.2	52.7	55.4	55.8	53.4	44.2	33.8	23.2
1860	34.5	34.2	35.4	38.3	45.3	50.0	57.0	55.0	51.1	44.6	41.2	31.6
1859	32.9	27.1	34.0	39.4	43.7	51.3	53.1	53.2	50.5	39.7	28.4	36.1
1858	28.0	27.7	35.6	39.9	45.9	50.4	53.4	53.4	49.6	43.5	39.6	27.9

Table A.1. continued

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1857	28.9	28.9	36.5	42.4	47.5	50.7	53.2	54.9	50.2	44.8	41.2	36.9
1856	37.6	38.5	39.6	39.4	47.7	49.8	50.9	54.0	50.2	42.3	38.5	30.9
1855	–	–	–	–	–	51.1	54.9	–	–	–	–	–
1854	27.5	32.0	32.2	40.8	42.8	48.9	52.9	54.7	50.7	42.3	42.6	33.1
1853	32.9	35.6	35.1	40.5	46.9	47.8	51.4	52.5	50.0	42.4	17.8	34.5
1852	39.4	33.3	30.7	40.3	45.5	49.8	55.4	55.4	51.6	45.7	35.1	23.9
1851	29.5	34.2	36.3	42.1	48.2	51.1	54.7	57.4	51.4	48.2	41.4	28.8
1850	21.7	34.7	28.0	38.7	45.3	48.0	54.5	55.6	50.4	44.2	38.8	37.2
1849	26.1	25.3	29.5	–	–	48.6	52.2	52.9	49.5	43.9	38.5	31.6
1848	26.6	29.1	32.9	37.9	46.2	52.2	57.4	54.0	50.5	43.7	40.1	30.4
1847	–	–	–	–	47.1	51.1	53.8	55.9	49.6	43.3	35.8	34.0
1846	–	–	–	–	–	–	–	–	–	–	–	–
1845	33.3	29.1	36.5	41.4	47.7	51.1	55.4	57.6	49.5	45.1	37.0	40.8
1844	28.4	37.8	34.2	41.2	45.9	55.6	55.9	55.4	50.2	42.8	35.8	34.7
1843	30.0	26.6	35.2	39.9	45.7	51.6	53.8	54.3	49.6	45.9	37.8	36.3
1842	36.7	35.8	31.1	39.2	43.2	52.7	54.1	53.6	50.5	43.2	39.4	38.7
1841	35.8	38.1	40.5	42.1	45.3	54.5	57.0	55.6	50.2	45.3	41.9	35.8
1840	45.1	32.7	46.2	42.6	47.7	50.4	54.9	57.9	52.9	44.4	35.8	35.8
1839	32.2	43.3	38.1	44.4	49.6	53.2	57.7	60.1	56.5	47.3	44.2	41.4
1838	34.5	36.5	35.4	41.2	48.0	51.6	55.0	55.0	50.2	46.2	41.5	41.2
1837	40.8	40.5	41.4	43.3	50.2	50.9	53.2	55.4	50.4	48.0	37.8	36.1
1836	31.1	37.6	40.5	43.2	50.0	53.8	53.1	55.6	51.4	47.7	41.0	31.8
1835	38.5	37.8	38.7	41.9	45.9	50.5	53.1	54.1	51.1	41.9	40.3	31.6
1834	32.2	35.4	39.2	40.6	45.3	53.2	53.4	52.7	51.4	47.1	44.2	39.2
1833	39.2	35.4	40.8	43.9	46.9	54.0	57.9	60.1	55.0	49.6	45.7	35.6
1832	34.1	30.8	35.1	37.1	48.1	52.4	55.5	55.9	51.5	42.9	42.1	36.1